Lecture Notes in Electrical Engineering 965

Mikhailo Klymash · Andriy Luntovskyy ·
Mykola Beshley · Igor Melnyk ·
Alexander Schill *Editors*

Emerging Networking in the Digital Transformation Age

Approaches, Protocols, Platforms, Best Practices, and Energy Efficiency

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Foreword of Prof. Dr. habil. Dr. h. c. Alexander Schill, Chairman of Chair for Computer Networks at TU Dresden

This Lecture Notes book covers a broad range of leading-edge topics in the area of Emerging Networking (EmN). It is suitable as a textbook for advanced lectures in the domains of systems architecture, networking, and distributed platforms. Moreover, it can serve as a basis for research and development seminars and as an inspiration for the interested IT and Telco specialists looking for new challenges and developments. The authors have many years of experience as professors and lecturers in computer science and have already published a significant number of textbooks, journal contributions, and conference papers.

The book is based on the latest advanced research and close cooperation of the scientists from Germany, Ukraine, Israel, Switzerland, Slovak Republic, Poland, Czech Republic, South Korea, China, Italy, North Macedonia, Azerbaijan, Kazakhstan, France, Latvia, Greece, Romania, USA, Finland, Morocco, Ireland, and UK.

The book starts with an introduction into the principles of EmN with multiple smart applications based on 5G and Beyond technologies. Under the category Emerging Networking, we also cover the steadily growing diversity of unmanned scenarios, where the process automation grade is nearly 100%. Operative disaster networking (emergency networking), which appears at sites, aiding rescue troops, belongs to the above-mentioned problems, too.

The future EmN architecture includes the components of artificial intelligence, Blockchain, software-based networking with efficient network slicing, quality of service management, cloud computing support, and advanced security approaches.

Furthermore, in the age of Digital Transformations Smart Applications like Smart Shopping, supported via Internet of Things (IoT), contactless systems (RFID, NFC) and emerging combined networks (mobile, wireless, and fixed) become a fundamental challenge both for urban and rural environments. The book discusses the software and networking design of smart applications in dynamically changing domains, such as online shopping, smart shopping, and social shopping. Further aspects of EmN support for smart applications will be examined in the book, too, including smart energy, smart office, smart home, robotics, unmanned (aerial) vehicles and flying objects, as well as context-sensitive intelligent applications, which are aimed at domains such as traffic telematics, health care, and entertainment.

Moreover, EmN supports distributed intelligence across the combined mobile, wireless and fixed networks in the Edge-to-Cloud Continuum. Therefore, the book also examines 6G driving factors, features, and potentials in the mid-term. Topics include antenna and cell structures, as well as network software based on further network function virtualization (NFV), artificial intelligence (AI), and advanced cyber-security approaches like Blockchain (BC).

Altogether, the content of this book is surely technically interesting while still being rather practically oriented and therefore straightforward to understand. We would like to wish all readers successful studies and lots of inspiration by this useful textbook!

September 2022 Alexander Schill

Preface

This volume is a collection of the latest research on Emerging Networking deployment and appeared in close cooperation of scientists from Germany, Ukraine, Israel, Switzerland, Slovak Republic, Poland, Czech Republic, South Korea, China, Italy, North Macedonia, Azerbaijan, Kazakhstan, France, Latvia, Greece, Romania, USA, Finland, Morocco, Ireland, and UK. The authors of the chapters from this collection present their in-depth extended research results in the above-mentioned scientific area.

The volume consists of 37 chapters, a foreword, an introduction, conclusions, and this preface.

Chapter 1, presented by **M. Beshley, M. Klymash, I. Scherm, H. Beshley, and Y. Shkoropad,** is titled *Emerging Network Technologies for Digital Transformation: 5G/6G, IoT, SDN/IBN, Cloud Computing, and Blockchain.* The chapter starts with a discussion of the state of the art in the development of network technologies for the global digitalization of society, including new trends and future research directions. The importance and necessity of active development of network technologies are also emphasized. In particular, the top ten trending network technologies that will play an important role in a comprehensive digital transformation are highlighted. The authors have developed unique concepts and concise explanations of such emerging technologies as follows: the Internet of Things, software-defined networking, network function virtualization, (Docker) container networking, cloud computing, edge computing and AI, information-centric networking and services, time-sensitive and deterministic networking, 5G/6G (generation) mobile networks, AI-based networking, and many other contexts related to advanced communications. Furthermore, it is emphasized that all emerging network technologies discussed in this chapter should be combined to organize new digital infrastructures in different deployment scenarios and use cases. Only then will we be able to achieve the necessary capabilities to optimize the performance and efficiency of different infrastructures in the new era of digital transformation.

In Chapter 2, titled *A Framework for Context-sensitive Control-Loops with Roles* by **I. Schmelkin, A.Schill, and A. Kropp,** it has been established that the increasing complexity of modern information and communication systems in the context of digital transformation requires self-adaptive software that can autonomously adapt to changing business needs of users, changing work environments, and system failures. Control loops are one of the popular approaches to the design and implementation of self-adaptation in such systems, but existing solutions are characterized by unification for specific applications without flexibility and universality of usage. For this reason, the authors developed the framework as a basis for flexibly adding or adjusting functions in existing code when small changes to the managed system occur, or for replacing entire parts of control functions when large parts of the managed system are changed. The benefits of using the framework for various information technology tools are explained and demonstrated in detail, namely for monitoring distributed server architectures, for network switches and routers, embedded systems, and Internet of Things sensors. In the future, the authors' proposed solutions will allow software developers of control logic for information technology systems to ensure the universality of control coordination between different types of device elements by adjusting existing roles and introducing new ones.

Chapter 3 titled *The Impact of Smart Economy and Digitalization on Market Efficiency* and presented by **J. Smettan** is dedicated to the study of the current stage of global economic and social development, characterized by a significant impact of digitalization. The rapid development of information and network technologies has aroused an in-depth interest in the digital economy, as well as its impact on the evolution of the labor market. The digitalization era has opened new horizons for the creation of new forms of employment and new forms of enterprises. The above causes the need for research to study the impact on the economic efficiency of significant transformations of the labor market caused by digitalization. That is why the author emphasizes that the digitalization of the economy entails the use of artificial intelligence, robots, and cloud technologies in the production process, increasing the demand for workers with digital skills. However, the public administration system is not ready for such global changes. The rapid pace of digital technologies implementation in management and production processes increases the imbalance between the development of the national labor market and the digital economy. The formation of the global digital segment of the labor market is accompanied by economic and social contradictions, which are especially acute in institutionally underdeveloped countries. From the scientific point of view of the author of the section, the positive consequences of the digitalization of the labor market include the reduction of labor costs for companies and the emergence of new jobs and new professions that will be associated with information and communication systems. The negative ones include the lack of knowledge of how to benefit from automation, the problem of ensuring the confidentiality of digitized data transmission, the loss of the country's competitive position in the market of goods and services, and the increase in income asymmetries between the rich and the poor. Thus, taking into account the strengths of the massive introduction of the latest information technologies in society, informatization is becoming such an important factor in increasing productivity and improving the quality of life that the changes that are taking place are considered by researchers as the onset of a new era of economic development, which in the literature is characterized by the term "Smart Economy".

Chapter 4, titled *Self-Driving Cars* by **A. Luntovskyy, D. Guetter and A. Masiuk**, discusses the importance of the construction of unmanned vehicles in smart automotive industry, which is rapidly evolving from technological proprietary development to digital transformation based on the use of Emerging Networking. The consumers' demands on the functionality of their cars are growing steady. Therefore, digital transformation in the automotive industry is becoming increasingly more important and market attractive. The authors emphasize that the cars of the future will be autonomous and electric, driven by emerging technologies such as artificial intelligence (AI), Internet of Things (IoT), and 5G functionalities. Thus, vehicles will be able to learn and predict the behavior of their customers, recognize signs, and make fast self-driving decisions. The chapter discusses important challenges that may arise when innovating the digitalization of transport in the era of digital transformation. In particular, it is argued that modern smart cars collect information about traffic patterns, drivers, their usual location, etc., through technologies such as IEEE 802.11p/ pWLAN/ pWi-Fi, ITS-G5/Car2Car, LoRA WAN, LTE CatM, and NB-IoT. This data is useful for interaction and communication with drivers and traffic management information and analytical centers based on Emerging Networking including proven fog and cloud technologies. However, to protect driver information (security) and personal data (privacy), the connected systems must be safe. That is why manufacturers and scientists are always looking forward to new methods in the area of cyber-security and network data defense.

Chapter 5, under the title *Smart Home: Protocols, Platforms and Best Practices* by **D. Guetter and A. Luntovskyy,** is dedicated to the development of modern digital platforms for smart homes. Scientific and technological progress and digitalization are moving at a very fast manner, making life easier, more convenient and better. One of such innovations is the construction of a smart home based on advanced network technologies. Wireless data transmission technologies have become widespread: Bluetooth, Wi-Fi, ZigBee, LoRa, NB-IoT, and other. In this chapter, the basic concepts for so-called smart home systems are investigated, existing protocols for the construction of "smart home" are considered, as well as design schemes are presented. The authors solve some practical problems of compatibility of network and IoT components as well as consider pros and cons for conformity and independence from the vendor's and cloud functionalities. Some issues of bottlenecks in existing platforms in terms of network security and data privacy are presented.

In Chapter 6, titled *Construction and Methods for Solving Problems at the SDN Control Level* by **O. Romanov, M. Nesterenko, G. Boggia, and D. Striccoli,** the authors have focused on improving the efficiency of SDN functionality, which is a key technology for the implementation of the overall concept of digital transformation by telecom operators. Transferring the management to a central controller, which understands the full topology of the network, allows to increase the efficiency of utilization of all connections and optimally utilize the resources of hardware devices. To obtain optimal solutions in the network resource management process, the authors formalize a number of mathematical management models. The solution of mathematical models allows obtaining numerical values of throughput and quality of service indicators in different modes of network operation. Such models provide an opportunity to compare the effectiveness of various methods of resource management using input data of real indicators of telecommunication network functioning. In particular, the comparison of these methods on criteria of quality of service in various scenarios of service and traffic transfer, taking into account such aspects as routing of flows, load balancing, and distribution on priorities, is carried out.

In Chapter 7 under the title: *Research and Implementation Directions of the Fast ReRoute Facility Backup Scheme in Programmable Networks* by **O. Lemeshko, O. Yeremenko, M. Yevdokymenko, S. Harkusha, and Y. Dobryshkin,** noted that in the context of digitalization of society, in addition to the requirements for quality of service (QoS), which have already become classic functions in modern digital infrastructures, the functionality to ensure a high level of fault tolerance and network security comes to the fore. This is especially important in the functioning of information and communication networks in conditions of constant external and internal factors of influence, which lead to a significant change in both structural and functional parameters and properties of the telecommunication network: its topology, throughput, manageability, stability, etc. Protocol routing and traffic management tools in digital infrastructures are the key technological means of ensuring QoS, fault tolerance, and network security. The authors proposed the newest fault-tolerant routing for the emerging technology of software-defined networks, which in the near future will be the key to digital transformation for Internet service providers, cloud operators, and enterprises in the era of digitalization. The novelty of routing lies in the updated form of the objective function in the optimality criterion, which is formed as a route metric that aims to minimize the use of additional network resources associated with the protection of network elements and the implementation of backup routes. In the course of the study, it is proved that the use of the proposed routing allows to reduce the resource consumption of the solution by 23% compared to the implementation without the use of the object redundancy scheme. It is shown that the implementation of the FRR solution, which prevents the inclusion of the protected network element in both the main and backup routes, can lead to a significant reduction in the throughput of the main route (up to 75%), which is used before the failure of the protected network element.

Chapter 8, titled *Ecosystem for the Development and Testing of Emerging Network Applications in 5G and Beyond Environment* by **R. Odarchenko and E. Shapira,** is devoted to applying the 5G wireless standard in modern ecosystems. Really, among the different novel wireless technologies, the decisive role for critical applications (automotive and PPDR) is given to the fifth generation mobile technologies. 5G is a key driving force in the development of the ICT industry and other related vertical industries. In these conditions, when a large number of commercial 5G networks are already deployed, software developers begin to develop a large number of network applications for the needs and with the use of 5G. Therefore, it is very important to support developers, small and medium enterprises in order to automatically test, certify, and bring to the end customer already debugged applications that can be deployed and used in commercial projects. The chapter presents the ecosystem for the development and testing of emerging network applications in the 5G and Beyond environment. This ecosystem combines software developers, test sites in European cities, automated testing and certification tools, end customers (users) of network applications, and other tools and systems. And it is mandatory to use NetApp Store, a specially developed Marketplace, to bring fully tested and certified network applications to the end user or customer. This paper also demonstrates how the methodology developed in the project will be applied in practice on the example of remote human driving NetApp. In particular, the architecture of the application, the principles of interaction with the test platform, the requirements for the application, the test plan, and metrics to be collected were shown. The chapter has a practical focus and can be of great interest to designers of environmental control systems. All aspects of the problem of designing ecology systems on the base of 5G standard are analyzed in the chapter scrupulously, and corresponding conclusions have been made.

Chapter 9 under the title: *Comprehensive Approach for Radio Equipment Design to Ensure Reliable UAVs Operations* by **L. Uryvsky, A. Gnashchuk, S. Osypchuk, and A. Moshynska,** is addressed to the peculiarities of providing a comprehensive approach for radio equipment design for modern unmanned aerial vehicles (UAVs). The functioning of UAVs is needed as a modern and promising technological object in various society applications and requires not only the means of direct flight support (aerodynamic properties, fuel resources, etc.), but also does require comprehensive radio equipment. The following tasks are expanded in this work and need qualitative solutions for building comprehensive radio equipment, such as reliable channel for UAV position registration on UAV, UAV position registration channel at the ground control center, transmission channel for flight control commands, and channel for collecting data for which the UAV is authorized. The chapter analyzes the needs of modern UAVs in providing them with radio and telecommunication systems that monitor the state of UAV parameters, determine its location, control the UAV operations, and exchange information with UAVs via duplex channel, information protection during information transmission, electronic warfare, and others. A comprehensive approach to the design of a multifunctional radio communication system to ensure the reliable UAV operations, algorithms for its operation to ensure the UAV functioning, depending on the type of tasks for which it is intended.

Chapter 10, titled *Networked Simulation with Compact Visualization of Complex Graphics and Interpolation Results* by **I. Melnyk and A. Luntovskyy,** is devoted to the methods of presentation of complex 2D and 3D graphics in Emerging Networks. The researchers and engineers of Emerging Networks provide efficient networked simulation and use visualization tools. Modern design and simulation systems as well as multiple practical scenarios frequently use the complex plane and spatial graphics, which is oriented on compact presentation of figures with complex geometry. It is especially important for CAD/CAM systems, where the complex constructions of elaborated machines or devices are simulated. Presentation in compact form of details with complex geometry is necessary for defining mechanical stresses, temperature distribution, or electromagnetic fields distribution by solving the sets of differential equations. In the theory of communication systems, interpolation of digital signals is necessary for defining the time of its transmission through a communication channel. In network cloud simulation systems, suitable interpolation functions for the figures with complex geometry are also necessary for reducing the amount of necessary digital data and its fast transmission through communication channels. In this chapter, interpolation of complex plane and spatial curves with using Bezier curves, Levitan polynomials, and Rvachov functions is considered. Possibility of applying arithmetic-logic functions for describing the figures with complex plane geometry is also considered. Corresponded examples for different interpolation functions are also given.

Chapter 11 under the title: *Digitalisation in Shopping: An IoT and Smart Applications Perspective* by **O. Cvetkovski, P. Gkikopoulos, and J. Spillner** demonstrates the development of a smart and cost-effective shopping application using Internet of Things (IoT) innovations. Such a system is suitable for use in different stores, providing customers with better shopping knowledge and time saving. The chapter provides a broad overview of ideas for using smart shopping in everyday life. It also describes unique concepts of evolution of architectural solutions together with research on software, hardware, and the latest network technologies. The information system of smart shopping proposed by the authors allows one to find the nearest route to get the listed products on different shelves in real time. The developed system was tested in the field of smart shopping. The experiment was conducted to ensure accurate determination of the proximity between the consumer and the product. The conducted experience describes how to apply known methods relying on wireless signal power to the field of smart shopping, where beacon signals are available from electronic shelf labels (ESL). Technical recommendations for the use of the proposed shopping information system in the conditions of various external and internal factors of influence, based on real research, are formed. In the future, it is expected that the innovative, scientifically based solutions of the authors of this chapter on smart stores can be transferred to smarter cities and regions.

Chapter 12 is titled: *Increasing Functional Stability of Telecommunications Network in the Depressed Zone of HPS Reservoir* by **P. Anakhov**, **V. Zhebka**, **L. Berkman**, and **V. Koretska.** The authors have analyzed the possibilities of applying HPS for defense of communication systems. The sphere of influence of the reservoirs of large HPS involves colossal massifs of rocks. The complex of geophysical fields and processes, mechanical and electrical transformations caused changes in the geophysical situation of the local environment in the depressed zone, which determined the need to formulate recommendations for the protection of telecommunications. A method for developing measures to protect the Emerging Telecommunication Networks from the effects of destructive influences, which includes data collecting of their impact on hardware resources, their analysis, and development of appropriate countermeasures. The conditions of functional stability of the Emerging Telecommunication Networks are formulated. They are represented by the resistance of the network infrastructure components to the impact of hazards, the ability to reconfigure the operational systems, and the transmission network. To verify network protection measures, a matrix of compliance with the threats has been developed, the occurrence of which may be due to processes in the depressed zone.

Chapter 13, titled *Discrete Vehicle Automation Algorithm Based on the Theory of Finite State Machine* by **I. Melnyk**, **S. Tuhai**, **M. Surzhykov, and I. Shved,** considers the model of vehicle control for the linear law of change of its speed in time. Corresponded mathematical models are created using analytical methods of discrete mathematics, set theory, finite state machines theory, and mathematical statistics. Based on the analysis of a simple law of motion of a vehicle between two given points in a straight line with a constant decrease in speed, it is theoretically substantiated that the mathematical model of such a law of motion can be realized in space of finite states over time. Such a simple algorithm is very suitable for smart-driving cars. An advantage of the proposed mathematical model of the vehicle control system is its simplicity, as well as the lack of corrective action at those times when the vehicle movement corresponds to the specified law with a slight error. This avoids unnecessary release of vehicle speed and oscillating processes that can occur in the case of a continuous control action if the control system parameters are selected incorrectly. Mathematical models for cases of quasi-stationary and random perturbing action are considered separately, and Student's distribution law is used to model random perturbation.

Chapter 14 is titled: *A Modified Federated Singular Value Decomposition Method for Big Data and ML optimization in IIoT Systems* by **O. Hordiichuk-Bublivska**, **H. Beshley**, **M. Kyryk**, **Y. Pyrih**, **O. Urikova, and M. Beshley.** The chapter is devoted to developing new digitalization methods for industrial systems based on big data, IoT, and machine learning technologies, which significantly contribute to the current stage of economic and social development. Data storage, processing, and transmission in digital format have become important attributes of the processes of production, distribution, exchange, and consumption of industrial products. The main conditions for successful digital modernization of industrial systems can be considered the effective use of the main advantages and minimization of risks and possible negative side effects of the implementation of information and digital technologies in the processes of production and sale of industrial products. The authors proposed a method of federated machine learning, which is implemented on industrial end devices. This approach allows the increase of industrial systems efficiency in the context of digital transformation. For data optimization and fast operation of machine learning, it is proposed to use the SVD algorithm, which allows the detection of redundant data and does not take them into account in further processing.

To increase the confidentiality of data transmission, an improved federated method of Singular Value Decomposition is proposed. This method involves the generation of all parameters for masking directly on local devices. The study results showed high accuracy of calculations by the proposed method and ensures the reliability of the data obtained. Based on simulations, it is proven that the proposed method allows optimization of big data and ML processing in industrial systems, which reduces the duration of calculations and makes it possible to make important decisions quickly. The authors also propose to use the Funk-SVD algorithm to increase the efficiency of sparse data processing in intelligent industrial systems.

Chapter 15 under the title: *Smart House Management System* by **B. Zhurakovskyi, O. Nedashkivskiy, M. Klymash, O. Pliushch, and M. Moshenchenko** describes in detail the process of developing a smart home control system using automation devices from different developers, solving the problem of interaction and data exchange in a heterogeneous digital environment. The authors have created their own Telegram bot for such an information system, which will allow the user to communicate with the IFTTT automation service, which communicates with the services of home automation device developers. An algorithm for combining the interaction of end systems into one interface with a detailed explanation of the functioning has been developed. The system is created using the Telegram messenger, which acts as an interface and protects the system using TelegramID. The system includes a Chatbot, a database, IFTTT system, and Web services of developers. At the same time, the developed system will have a large extension in the form of a new interface and several additional automation scenarios by adding triggers based on user interaction with the mobile device and the environment.

In Chapter 16, titled: *Searching Extreme Paths Based on Travelling Salesman's Problem for Wireless Emerging Networking* by **O. Pavlenko, A. Tymoshenko, O. Tymoshenko, A. Luntovskyy, Yar. Pyrih, and I. Melnyk,** the problems of finding the optimal route in the network with fully connected topology by solving the Traveling Salesman's Problem (TSP) are considered. Nowadays, the world is characterized by Emerging Networking in various areas of human activity and industries. Among the combined networks of today (mobile, wireless, fixed), the networks with a fully connected topology occupy a special place. They play an essential role in the software agents interacting with each other according to the point-to-point (P2P) model, the machine-to-machine (M2M) communication model for robotics and IoT with a specified gateway, energy-efficient clusters, or data centers with a large number of central processing units and radio channels between them, as well as Multiple Input Multiple Output (MIMO) antennas for the 5G and Beyond standards. Typically, the analysis of network systems with a fully connected topology leads to solving the TSP. A solution, however, requires combinatorial enumeration and needs a massive amount of computing time, even on powerful modern computers (NP-complexity). The given work provides a new TSP algorithm, which is based on the analysis of the digital series by unique sums. That allows one to find the best route between network blocks with a fully meshed topology. The obtained simulation results and computational experiments have shown the very high efficiency of the proposed algorithm. Furthermore, an attempt for a specific TSP-based MAC protocol is herewith offered (OSI layer 2), which distinguishes it from existing routing protocols (layer 3) such as OSPF+BGP or RIP

+BGP and above (with QoS considering). The considered TSP-based MAC protocol for wireless sensor network (WSN) provides access from a start node (cluster head, gateway) to all other nodes within the limited small net (cluster). The start node can be selected dynamically for future reconfiguration for energy efficiency and long life without frequent battery exhaustion. The start node provides TSP-based polling to all other networking energy-autarky nodes within the cluster. The obtained results are very important both theoretically and practically for forming novel network protocols.

Chapter 17, under the title: *A Survey of Intrusion Detection Methods in Wireless Networks* by **A. Babaryka, I. Katerynchuk, and I. Chesanovskyi,** focuses on the fact that the use of wireless networks for digital transformation is one of the most popular and, at the same time, sensitive to various types of cyber-attacks. If information is transmitted through wires in traditional networks, the radio waves used for wireless solutions are quite easy to intercept with the appropriate equipment. The principle of wireless network operation leads to many possible attacks and intrusion vulnerabilities. The paper describes the characteristic vulnerabilities of wireless networks and, based on these properties, identifies several possible types of attacks on wireless networks. Based on the analysis of modern research in the field of security of information systems, the classification of intrusion detection systems by monitoring methods, the nature of the response to threats, the nature of the data processing process, security levels, time characteristics, data processing location, and the type of anomaly detection is proposed. In particular, the authors describe that intrusion detection system (IDP) provides an additional level of protection for wireless networks together with the intrusion prevention system (IPS). IDS can notify about the beginning of an attack on the network, and some can detect previously unknown attacks. IPS is not limited to alerting but also takea various measures to block the attack (e.g., breaking the connection or executing a script specified by the administrator). Most intrusion prevention systems use one of three detection methods: signature, a statistical anomaly, and protocol analysis state. Studies have shown that at the present stage, models based on neural networks can be used quite effectively to block hybrid attacks. Such systems are quite easily implemented in existing tools, can adapt training, and can work with large amounts of data, which is important when processing network traffic.

Chapter 18, titled: *Applied Steganographic System for Hiding Textual Information on Audio Files* by **S. Buchyk, S. Toliupa, N. Lukova-Chuiko, O. Khomenko, and Y. Serpinskyi,** is devoted to the development of effective methods of digital information protection, in particular methods of computer steganography and steganalysis, which are relevant and important in the era of digital transformation of the state and society. The subject area is analyzed, the existing methods of audio steganography are considered, their advantages and disadvantages are analyzed, and their comparison is carried out. The authors analyzed the reduction of significant changes to the container files and to increase the resistance of containers to attacks. Based on the analysis, it was decided to develop a modification of the least significant bit method because this method provides greater security and is an effective way to hide secret information from hackers and send it to the destination safely and safely. The LSB steganographic algorithm for hiding textual information in audio files has been enhanced by the additional use of a cryptographic method and pseudo-random numbers to create a stable crypto key. Also, the algorithm ensures that the file size does not change even after encoding and is also suitable for any type of audio file format. This algorithm also allows to hide much more secret information in container files compared to other algorithms. The proposed improved algorithm can be used in next-generation networks. It makes sense to use the method to build covert network channels in the new network environment, for example, covert channels based on streaming media networks or covert channels based on IPv6 networks.

Chapter 19 is titled: *Reliability Assessment of UAV Fleets* by **E. Zaitseva, V. Levashenko, N. Brinzei, A. Kovalenko, M. Yelis, V. Gopejenko, and R. Mukhamediev.** The authors proposed the method of simulation unmanned aerial vehicles (UAVs) fleets, based on an approach of binary-state system. UAVs are widely used in various industries for monitoring, searching, communication, etc., which is a very interesting and constantly improving direction in the era of digital transformation. The proposed method can be used to analyze homogeneous and heterogeneous fleets that have different types of management. The proposed readiness definitions for different types of UAV fleets allow to analyze the reliability of fleets with reduced computational complexity. This chapter presents models for assessing the reliability of a UAV fleet managed centrally or decentralized. The following topologies are considered: homogeneous redundant UAV fleet, homogeneous hot redundant UAV fleet, heterogeneous redundant UAV fleet, heterogeneous hot redundant UAV fleet, and heterogeneous hot redundant UAV fleet. For the listed topologies, reliability estimates are obtained depending on the number of primary and backup UAVs.

In Chapter 20 under the title: *Method of Cyber-Resilience Information-Control System Synthesis of Mosaic Structure* by **Yu. Danyk** and **V. Shestakov,** authors make a significant contribution to the further development of cyber-physical systems, which are a key technological component of the Industry 4.0 concept. Cyber-physical systems allow to receive and control information for automation and virtualization of processes, to influence production systems, and to determine the number of employees required to meet the needs of production within the concept of Industry 4.0. The section presents the results of the development of the model and method of synthesis of cyber-resilience of the information control system of the mosaic structure. The model and method of ICS synthesis allow to automate the process of determining the rational structure and characteristics of automated workplaces of cyber-resistant ICS. At the stage of structural and parametric synthesis of the method, the mathematical apparatus of multicriteria optimization by a nonlinear trade-off scheme is used. According to the results of the research carried out by the authors during the deployment of a cyber-physical specialized center for the operational control of forces and means, using the developed method, an increase in its cyber-resilience was obtained in the range of up to 95-98%.

In Chapter 21 under the title: *Neural Network Architecture with Oscillatory Synaptic Blocks for Signal Processing of Spatially Spaced Multiband Radar Complex* by **R. Peleshchak, V. Lytvyn, I. Peleshchak, and O. Veres,** the authors develop a neural network method of radar target recognition based on a spatially distributed multi-band radar complex, which is an important area of information technology. The proposed complex consists of spatially distributed radar stations that conduct joint radar target detection. The main idea of a multi-band radar complex is that radar systems operate at different frequencies with different polarization and are located in different places. This allows to simultaneously detect dozens of radar targets and recognize them in real-time using a neural network with parallel blocks of oscillatory synaptic connections. The input features for recognition are target scattering diagrams, which are integral characteristics of effective target scattering zones. Based on the modeling, it was found that air objects with the largest effective target scattering area have the highest probability of correct target recognition. As the signal-to-noise ratio decreases, the probability of correct target recognition decreases.

Chapter 22, titled *Modeling, Simulation and Visualization of Acoustic Coherent Images* by **I. Hvozdeva and V. Myrhorod,** is devoted to the consideration of methods for creating mathematical models of acoustic coherent images in relation to the tasks of monitoring the underwater environment of the World Ocean using modern distributed information and telecommunication networks. The combination of the theoretical approach to constructing an acoustic image as a section of the secondary field at the aperture of the receiving antenna and the experimental method for obtaining such images with instrumental measuring instruments of a hydroacoustic tank was chosen as the main research method. Comparison of theoretical and experimental results makes it possible to verify the proposed mathematical models of acoustic coherent images. The proposed models, confirmed experimentally, make it possible to perform computer simulation of the processes of formation and processing of acoustic coherent images (ACI) to solve the problems of creating and improving methods for processing such images for their recognition and classification, as well as for testing the technical means of underwater monitoring networks during their tests.

Chapter 23 under the title: *5G and Beyond: Perspectives of 6G* by **A. Luntovskyy** examines 6G driving factors, features, and potentials in the mid-term. Further development will concern better coding and spectral efficiency, new antenna, and dense heterogenous cell structures. A special meaning has the use of network softwarization based on further network function virtualization (NFV), interoperability with existing terrestrial and non-terrestrial solutions, as well as deployment of advanced cyber-security approaches like Blockchain (BC). Convergence with non-terrestrial services like Starlink in the giga-cell area is possible in mid-term too. Emerging mobile and wireless networks provide herewith the best QoS (higher data rates and lower latencies). The significant growth of channel power and spectral efficiency promise approaching to the known Nyquist–Shannon's limits (post-Shannon metaphor). Mid-term 6G networks include, moreover, further "enabling technologies" with better than for 5G sensing and passive localization techniques, when the distance and their derivations (velocity and acceleration) can be efficient determined via evaluation of the propagation delays due to reflections on the objects (radar techniques, WLANp, VLC, UWB, LiFi) in multiple smart applications for unmanned PHY objects and vehicles.

In Chapter 24, titled *Method and Means of Synthesis of Barker-Like Codes for Data Transmission Coding* by **O. Riznyk, I. Tsmots, and V. Teslyuk,** the authors investigated possibility of increasing the noise immunity of data transmission in communication networks by using barker-like codes. Improving noise immunity at fixed data rates is an urgent problem for emerging wireless networks in the era of digital transformation. The method of synthesis of noise immune barker-like code sequences using ideal ring beams is improved. The method of a fast finding of such noise immune barker-like code sequences, which can find and correct errors to the greatest extent according to the length of the received code sequence, is improved. The algorithm for fast finding of noise immune barcode sequences, which are able to find and correct errors in the greatest number according to the length of the received barcode sequence, is implemented. The simulation model of noise immune barker-like coding using ideal ring beams is developed. The simulation model of noise immune barker-like coding for search and correction of errors in the obtained noise immune barker-like code sequences was implemented. The presented noise immune barker-like code sequences have practical value, as the resultant barker-like code sequence contains up to 50% and corrects up to 25% of distorted symbols from the length of the noise immune barker-like code sequence.

In Chapter 25 under the title: *Processing Marker Arrays of Clustered Transformants for Image Segments* by **V. Barannik, A. Krasnorutsky, V. Barannik, Yu. Babenko, S. Shulgin, O. Chernenko, O. Slobodyanyuk, and M. Bondarchuk,** the authors proposed an innovative technological approach to the preservation of the information component of video data in the aerospace segment of the remote video service. The imbalance between the reliability of the retrieved video image and the efficiency of its delivery by onboard data transmission channels is substantiated. On the basis of the structural characteristics of the binary representation of the clustered component, a method of forming markers and a marker array of clustered transforms of the image segment are developed. It is substantiated that in order to reduce the volume of clustered transforms, it is necessary to reduce the volume of marker arrays. This approach allows to reduce the structural description of the linearized marker array of clustered transformants by reducing the number of repeating markers. A method of forming a sequence of two-component tuples containing the length of the cluster trend that precedes the corresponding marker is developed. This approach allows to reveal structural regularities in arrays of markers due to the presence of cluster trends. It is substantiated that there is a relationship between the components of tuples, which is due to the positions of the markers in the linearized array of markers, and hence the correlated lengths of the marker chains. For a structural approach to the processing of tuples, a method of forming domains for the marker matrix is developed, which takes into account the correlation of the lengths of the marker chains.

Chapter 26, titled: *A Method of Scrambling for The System of Cryptocompression of Codograms Service Components* by **V. Barannik, S. Sidchenko,D. Barannik, M. Babenko**, **V. Manakov**, **O. Kulitsa, V. Kryshtal, V. Kolesnyk,and O. Kuzmin,** is devoted to the advanced method of scrambling for a service components system in cryptocompression codograms formed under the condition of discarding the pixel brightness values in RGB space least significant. Such approaches are useful for Emerging Networking with the increased modern demands on content security for smart applications. The method provides an increase in the availability of video information due to further cryptocompression representation of image volume reduction; increase in crypto resistance by changing the values of the service elements of the data system, breaking the correlation between the elements and changing the pixel frequency. The method of crypto-resistant compression of codograms of service components of the scrambling system, formed under the condition of discarding the least significant bit in the values of pixel brightness in RGB space, is developed. The difference of this method from the known ones is that before performing scrambling transformations, the merging of service data presented in a reduced dynamic range into 8-bit combined elements is organized. At the stage of permutation of the merged 8-bit data, not only the location of the values of the original 7-bit elements of the service components is organized, but also the change of their values. This allows to increase cryptographic characteristics of known permutation transformations. The software implementation of the method of scrambling the system of service components in codogram cryptocompression provides formation of a secure design of codogram of crypto-resistant compression with scrambled service components.

Chapter 27, titled *Smart Ergonomic Lighting for Circadian Rhythm* by **Ye. Zheliazkov and J. Jamnenko,** addresses the important scientific and applied problem of lighting characteristics for the human visual and the circadian systems for designing light intensity and color for various healthcare and medical applications. An algorithm of defining human circadian rhythm has been elaborated as well as electrical scheme of corresponded adaptive device based is proposed.

In Chapter 28 under the title: *The Approach to Assessment of Technical Condition of Microprocessor Systems that are Implemented on Integrated Circuits with a Programmable Structure* by **S. Shtanenko, Yu. Samokhvalov, S. Toliupa, and O. Silko,** the problem of diagnostics of programmable logic device (PLD) microprocessor systems is the basis for building complex technical systems operating in adverse conditions, including cyber-attacks. A significant advantage of field-programmable gate array (FPGAs) is their versatility and the fact that they can be quickly programmed to perform the functions of almost any digital device. The use of FPGAs as an element base for the construction of modern microprocessor systems today is a promising direction in terms of designing highly reliable, fault-tolerant complex technical digital systems that operate in adverse conditions, including cyber-attacks. The analysis of existing methods of testing integrated circuits with programmable structures is carried out, and their advantages and disadvantages are noted. It is proposed to use a service processor as a diagnostic device as an integral element of a multiprocessor system. This processor will not only collect diagnostic information but also make decisions about the reconfiguration of the system to restore its functioning in automatic mode by reprogramming the PLC. In general, the proposed approach to diagnostics of microprocessor systems based on FPGA is a further development of the self-diagnostic method. If a complex technical system is given the property of adaptation to changing operating conditions, then such a system can be considered as a system with elements of artificial intelligence.

Chapter 29, titled *Robust Approach to the Signal and Data Processing* by **I. Prokopenko**, is devoted to the development of the theory of robust methods for signal and data processing construction of space distributed information-measuring systems in their distortion by non-Gaussian impulse interference and failures of the recording equipment, purposed for Emerging Networking. The problem of robust estimation of regression parameters of a random process is considered, the recurrent algorithm of gradient search of the solution of plausibility equations for non-Gaussian perturbations with density of distribution of Tukey type is synthesized, and their efficiency is investigated.

In Chapter 30 under the title: *Automation of Vehicle Control Systems and Emerging Networking* by **Yu. Zaychenko, S. Melnykov, G. Hamidov, A. Gasanov, and P. Malezhyk,** the issues of organization of intelligent vehicle control systems, including those using the capabilities of Emerging Networks, are considered. Directions for the organization of automated and intelligent control systems are shown. The main stages of automation of control systems for dynamic objects and the evaluation of the effectiveness of control functioning are determined. As a result of the provided review, the characteristic levels of development of the intelligence of control systems are presented, the features of emerging networking are highlighted, and the effectiveness of the above ideas for solving practical problems is shown.

Chapter 31 is entitled: "*Metaverse of Things in 6G Era: An Emerging Fusion of IoT, XR, Edge AI and Blockchain Technologies*" by **T. Maksymyuk, J. Gazda, B. Shubyn, O. Karpin, O. Kapshii, O. Urikova, El-M. Amhoud, M. Liyanage, M. Jo, and M. Dohler**. The authors describe an interesting paradigm of synchronized physical and virtual realities within the Metaverse of Things (MoT). The prerequisites and demand for the user interoperability across real and virtual world are described. Authors describe the key elements of the MoT, namely immersive vision, pervasive sensing, ubiquitous computing, comprehensive intelligence, and decentralized trust. The relation among those elements and the corresponding underlying state-of-the-art technologies within the MoT are clearly outlined. The chapter also pays a reasonable attention to the underlying 5G/6G networks architecture, which should orchestrate a large number of data flows associated with the MoT applications. The interesting insights are given toward the fact that emerging 6G networks should be able to synchronize humans, things, and digital twins across real and virtual worlds in real time. This can be achieved by augmenting visual and sensory information from the real world and transferring it to the digital twins in the metaverse via multiple synchronized data flows. In the opposite direction, virtual actions in the metaverse should be translated to the real IoT devices in the physical world. To tackle this challenge, authors define the 6G architecture with decentralized service management via Blockchain. Particular feature of the proposed vision is that each user is able to adjust his quality requirements for each device and select the best network operator for each data flow independently. In this case, the synchronization and timely scheduling of data flows are ensured by the smart contracts and non-fungible tokens, according to the specified preferences of each user. The vision, provided in the chapter, opens a wide range of previously unimaginable use cases in the emerging 6G era.

Chapter 32 under the title: *Data Management in IoT: from Sensor Data to Intelligent Applications* by **V. Vasyutynskyy and A. Luntovskyy** is devoted to new solutions in Emerging Networks, including cloud computing and data mesh. Globalization processes and digitalization, which lead to the use of emerging network technologies IoT, artificial intelligence, big data, data analytics, cloud technologies, and robotics, provided an opportunity to analyze large amounts of data in a short period of time, which radically modifies approaches to digital transformation. Emerging networks allow the smart devices and applications to connect efficiently and everywhere, opening a lot of opportunities and use cases for getting and using data. The resulting huge amount of heterogeneous data leads to new challenges in data management, like data storage, processing, privacy, life cycle, etc. This chapter provides an overview of these challenges and modern solutions such as cloud computing and mesh data networks.

Chapter 33 is titled: *A Neuron Network Learning Algorithm for the Recognition of Fractal Image and the Restoration of their Quality* by **O. Yunak, B. Strykhaliuk, M. Klymash, Y. Pyrih, and O. Shpur.** The chapter focuses on one of the most up-to-date tasks in the field of information technology in the context of global digitalization of society, namely intelligent image recognition. Fractal images are often used for graphical representation of data during computer modeling of some processes, for automatic generation of abstract images, in particular entertainment applications. Fractal graphics are contained in scientific visualization packages for building both simple structures and complex illustrations that simulate natural processes and three-dimensional objects. Recognition of fractal structures is one of the most difficult tasks, and this is due to the fact that it is very hard to collect data, since the construction of fractal structures requires significant information computing and resources. To solve this problem, the authors used the RSIF algorithm. The proposed algorithm does not use recursive functions and looping, which in turn requires fewer computing resources. The results of the algorithm showed that the use of neural networks allows to effectively recognize fractal images and to convert them into RSIF. The resulting RSIF matrix allows you to improve the quality of the fractal image and converts raster graphics into vector graphics, which in turn will allow you to resize the image without losing quality. In the future, this neural network can be integrated into pattern recognition systems and graphic editors in the form of a library.

Chapter 34, titled *Advances in Data Reduction Techniques to Solve Power Spectrum Estimation Problems for Emerging Wireless Networks* by **A. Lozynsky**, **I. Romanyshyn**, **B. Rusyn, M. Beshley, M. Medvetskyi, and D. Ivantyshyn,** discusses new trends and research directions for reducing redundancy in the spectrum analysis process for emerging wireless technologies, in particular 5G/6G. This research direction will allow future wireless digital infrastructures to improve coding resilience and ensure the efficient use of the spectrum of licensed signals, the lack of which is observed today. The authors proposed a technique for estimating the autocorrelation function (and power spectrum) of a stationary random signal for a finite sample under different variants of non-uniform data sampling. The main difference between the methodology and the known ones is the focus on minimizing the number of sampling data by reducing redundancy. For this purpose, the authors applied a reduction ruler to estimate the autocorrelation function and the power spectrum. New construction techniques based on the known Golomb ruler, based on irregular sampling with sampling frequency switching of two close frequencies, are presented. The approaches for implementation in practice are described in detail. Modeling of the estimation accuracy based on the calculation of the standard deviation, which tends to increase as the amount of data decreases, has been performed. It is proved that the proposed solutions will reduce the number of calculations in the implementation of digital signal processing for wireless networks, which are emerging in the new era of digital transformation.

Chapter 35 is titled: *Investigation of High-Speed Methods for Determining the Equilibrium State of a Network Based on the Principle of Maximum Entropy* by **R. Politanskyi, A. Samila, L. Politanskyi, V. Vlasenko, V. Popa, Yu. Bobalo, and I. Tchaikovsky.** In this chapter, the authors propose to use the entropy method to determine the most probable state of the network, which is subject to restrictions on the total traffic generated and received in each node of the network. It is also assumed that the network is closed, that is, the sum of all generated information flows is equal to the sum of all received flows. The possibilities of applying the method in networks with several decentralization planes are considered. The method of building a model of a decentralized network in the form of a two-dimensional sparse matrix of information flows, which is structured in a special way, is substantiated. Accordingly, the purpose of the analysis of a decentralized network is to determine the optimal value of the entropy of the system represented by such a matrix. A method for estimating the range of values of the entropy of a decentralized network by analyzing significantly unbalanced networks with a significant number of zero values in the matrix of information flows is developed. Calculations are presented for elementary configurations of the network represented by a flat graph and a decentralized network with the lowest topological complexity. The advantage of this method is the significantly lower computing power consumption for the analysis of the network state, even if the network has a complex decentralized structure.

Chapter 36 under the title: *Elliptical Polarized Radio Wave Decay in Land Communication Links* by **Y. Ben-Shimol, N. Blaunstein, and C. Christodoulou** is devoted to the topic of depolarization in terrestrial wireless communication channels, which is insufficiently studied even for technologies beyond 4G. An innovative analytical approach based on a multi-parameter stochastic model as a combination of the vision of radio wave propagation over the built-up area and a statistical description of the main characteristics of the terrain is presented. An approach is developed that provides a sufficient way to predict the depolarization attenuation of radio waves and allows to reduce of polarization losses in two-way terminal antennas, thereby achieving cheaper data transmission in wireless networks. The expression of the total wave intensity is proposed, and the probability distributions for the parameters describing the spatial ellipse of polarization, the distribution of energy along and across the propagation directions, as well as the change in the shape and spatial orientation of an elliptically polarized wave depending on the terrain features are obtained. These equations are based on a new physical view of the Stokes parameters and on test results that take into account real data of mixed radio communications in the residential sector and suburban/urban radio lines that are widely used.

Chapter 37, tilted *Fault Identification in Linear Dynamic Systems by the Method of Locally Optimal Separate Estimation* by **A. Volovyk, V. Kychak, A. Osadchuk, and B.Zhurakovskyi,** provides a new method of synthesis of two-stage structures for recursive filters. Due to the rapid development of so-called Emerging Networks of new generations, the problem of improving the stability and reliability of communication equipment has become very important. Emerging Networks support nowadays multiple smart applications, including industries, automotive, robotics, unmanned vehicles, and flying objects. They enable automation and "Distributed Intelligence" across the combined mobile, wireless, and fixed networks in the Edge-to-Cloud Continuum. Therefore, advanced efficient solutions for the synthesis problems for optimal filters are necessary. An advanced method is proposed in the chapter, which provides a successful realization of such filters. The presented synthesis method is based on the assumption that there is no a priori information about the dynamics of operating faults and disturbances. The provided synthesis method is based on assumption of the lack of prior data about fault dynamics and perturbations. In this case, it is assumed that faults affect both the state of the system and the output variables, and disturbances affect only the state variables. Synthesis of the recursive filter was made in two options. In the first case, it was assumed that the distribution matrix of faults in the observation channel is a full rank matrix, and then the result obtained was generalized to the case of an arbitrary rank matrix. The proposed filters are locally optimal in the sense of forming separate unbiased fault estimates and states with minimal variance. For these purposes, a matrix version of the Lagrange multiplier method was used. The operability of the considered method was tested on the example of an aircraft landing system.

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Introduction

Protocols, Platforms, Best Practices, and Energy Efficiency

Emerging Networking in the Digital Age: What does it mean and what is inside? Which paradigms are commonly used for Emerging Networking?

Emerging Networking (EmN) appears nowadays spontaneously and accompanies us in our everyday life as well as supports modern industrial processes, ongoing digitalization of workflows, and multiple smart office scenarios.

Such kinds of networks are based on up-to-date heterogeneous combinations of mobile, wireless, and fixed networks, which are augmented via ad hoc and PAN as well as IoT devices. The other important part of them is virtualization on the basis of well-known software-defined networking (SDN), which represents one of the most important paradigms for emerging networking.

Paradigms, per definition, are a set of concepts or design patterns, including theoretical and empirical models, research methods, practical tools, platforms, and standards, structure opportunities, what means a significant contribution to a field. We would like to study such paradigms for EmN in detail.

EmN supports distributed intelligence across the combined mobile, wireless, and fixed networks in Edge-to-Cloud Continuum.

Under category EmN, we also mean steady growing diversity of unmanned scenarios, where the process automation grade is nearly 100%. Operative disaster networking (emergency networking), which appears at sites, aiding rescue troops, belongs to the above-mentioned problems too. This is the next paradigm.

Intelligent vehicle automation algorithms based on analytical methods of discrete mathematics, set theory, finite state machines (FSM) theory, and mathematical statistics are developed. Such algorithms can be implemented on the sensors and onboard computers of the vehicles. They define the best time intervals, change the velocity and acceleration corresponding to the current situation on the road, and communicate to the central server, which generally controls the situation on the road. EmN can realize communication between the central server and onboard computers with built-in M2M (machine-2-machine) style, i.e., not only by Wi-Fi but also by LoRA WAN, LTE-CatM, NB-IoT, etc.

Together with the widespread Internet of Things (IoT) and digitalization challenges, EmN begins a new era in the history of networking, where the network itself is part of the digital environment, and IT translates business intentions into appropriate network configurations for all devices.

The EmN provides flexible network monitoring, performs network analytics, and demonstrates the full advantage of machine learning (ML). The EmN solutions enable better process automation and proactive problem solving as well as decentralized operation of the network infrastructure.

Furthermore, within the work, we would like to pay attention to the embedded systems in industries, entertainment, medicine, and smart office, where EmN offers many operations that can be performed automatically using intelligent control algorithms (artificial intelligence and machine learning).

As a result, network operation costs (OPEX), application response times (even up to real-time solutions), and energy consumption can be significantly reduced, network reliability and performance are improved, and network security and flexibility are enhanced. This will be a benefit for existing networks as well as evolved 5G and Beyond mobile networks, emerging Internet of Things (IoT) in cooperation with fog and cloud systems, and soon for the future 6G networks. The future mobile networks will reach a whole new level of self-awareness, self-configuration, self-optimization, self-recovery, and self-protection based on terrestrial and non-terrestrial (SAT-based) hierarchical and heterogeneous cellular infrastructures.

Embedded systems integration, modern electronic devices, and IoT deployment require an interdisciplinary approach as multiple technologies come together to the networked control algorithms, automation routines, and monitored workflows. Hence, an important part is the networked supporting tools for CAD/ CAM, modeling, simulation, and visualization of electronic signals and data processing.

The future EmN architecture includes the components of artificial intelligence (AI), Blockchain (BC), SDN, and network functions virtualization (NFV) with efficient network slicing, quality of service (QoS) management, supported via cloud computing, and advanced security approaches. So that is the next paradigm.

Virtualization, creating of “Digital Twins” based on SDN and NFV, on the other hand, can be considered as key technologies for EmN. SDN provides a programmability feature that is essential to facilitate 5G Beyond networks’ operation while reducing capital and operational costs (CAPEX/ OPEX). NFV allows network resources to be virtualized and decoupled from hardware platforms, facilitating programmatic enhancement of network functionality, thereby making the network easier to deploy and more adaptable to possible changes.

We would like to develop our knowledge not only in theoretical areas of EmN, but also deepen these in the fascinating practical scenarios: from industrial robotics to current environment protection under the use of AI-based systems to the robotic space management program. EmN means applying, testing, developing, and teaching using new “Smart Applications”, networked “Virtual Testbeds” for electronic devices, IoT, networked simulation and modeling tools. Do you have an interest in our work? Then you are welcome!

Furthermore, in the age of Digital Transformations Smart Applications like Smart Shopping, supported via IoT, contactless systems (RFID, NFC) and emerging combined networks (mobile, wireless, and fixed), become a fundamental challenge for urban and rural environments both. The work discusses the software and networking design of smart applications in such dynamically changing domains, such as the attractive apps for online shopping, apps for so-called smart shopping, and social shopping. Further aspects of EmN supported smart applications will be examined in the book too, inter alia, smart energy, smart office, smart home, robotics, unmanned (aerial) vehicles and flying objects, and context-sensitive intelligent applications, which are aimed at traffic telematics, health care, and entertainment.

Digitalization forces the markets to be more transparent and manageable. The psychological basis for decision-making by market participants is also being significantly changed through digitalization and smartness. The work examines, in particular, the characteristics of well-functioning markets and the possibilities of digital tools to generate or influence these characteristics.

With the emergence of new services and applications in the digital age, the networks are forced to satisfy a wide range of users and meet their needs in terms of end-to-end latency, reliability, and scalability, to promote the use of mobile devices and provide flexible and efficient network connectivity.

And, last but the least, EmN can support so-called Networked Ergonomics based on appropriate lighting and HVAC monitoring, aimed at the optimization of working environments and office communication.

With the development of EmN, customer needs and behavior have changed. The focus shifts from improving network performance to improving the perception of Quality of Experience (QoE). Providing according to the intentions of users of a given level of QoE for services and applications becomes a fundamental task in the implementation of end-to-end resource management in the known concept of intent-based networking (IBN).

The book examines multiple case studies and gives the answers to the critical questions about secured and Blockchain-supported as well as energy-efficient EmN and design paradigms. Summarizing, the following EmN features are considered:

- Small energy consumption and energy efficiency
- Wide interoperability to 4G, 5G and Beyond, WSN, RFID, NFC, Robotics, Wearable
- New efficient communications models with decentralization, i.e., M2M, fog-based models, P2P instead of convenient C-S or cloud-centric, but not only....

The work also examines 6G driving factors, features, and potentials in the mid-term. Further development of 6G in the frame of EmN will concern better coding, new antenna, and cell structures. A special meaning has the use of network softwarization based on further network function virtualization (NFV), artificial intelligence (AI), and advanced cyber-security approaches like Blockchain (BC).

The emerging mobile and wireless networks provide the best QoS (higher DR and lower latencies). The significant growth of channel power and spectral efficiency EmN promises leading to approaching known Shannon limits. The above-mentioned growth is based on:

- New radio access technologies (RATs)
- Dense heterogeneous cell structures
- Advanced spectrum spreading
- New modulation schemes
- Massive 3D-MIMO antennas and beamforming.

Future 6G networks include, moreover, further enabling technologies with better than for 5G sensing and passive localization techniques, when the distance and their derivations (velocity and acceleration) can be efficiently determined via evaluation of the propagation delays due to reflections on the objects (radar techniques, WLANp, VLC, UWB, LiFi) in multiple smart applications for unmanned PHY objects and vehicles.

Conventional network security approaches, which mean centralized solutions with service orchestration and 1:1 and 1:n paradigms and are filtered by the convenient firewalls, IDS/ IPS as well as use of public key method and PKI, are to be substituted via advanced approaches which prefer decentralized solutions, more flexible service choreography for P2P and n:n, as well as Blockchain technology and so-called Cooperative Intrusion Detection P2P Networking (CIDN).

EmN networking raises new challenges for researchers to investigate, redesign, and develop future intelligent network-based algorithms for Embedded Electronics.

The Distinguishing Features of the Book That We Feel Sets Our Book Apart From Others in the Field

- Multiple considerations of the EmN aspects based on modern approaches like IoT, IBN, SDN, NFV, smart office, and unmanned vehicles energy efficiency
- EmN can provide robust QoS and usual QoE as well as attractive, up-to-date content.
- EmN is deployed under the wide use of Blockchain technology.
- Any modern (fixed, radio, SAT-based, wireless, or mobile) vitalization technology can be configured and used as well as networking heterogeneity can be consolidated.
- EmN is energy efficient and economizing of CAPEX/OPEX, in mid-term also CO2 footprint minimizing.

- EmN content is, per definition, intrusion protected as well as workflow and transactions are secured via PKI and Blockchain as well as Cooperative Intrusion Detection P2P Networking.
- EmN is mainly used to transform users' business intent into a network configuration, operation, and maintenance strategies, which are prominent for designing the AI-enabled 6G networks.

We will provide you with a clearer demarcation of our own concepts for EmN, which are built on SDN, NFV, BC, and AI concepts with subsequent software implementation of network functions with a significant improvement in service quality, which feels like the usual Quality of Experience (QoE), which can be every time monetized. The protection against normal risks for networked data from intrusions is guaranteed. Such networks already create convenient conditions for reducing their cost and the cost of their operation (the expenditures, namely CAPEX and OPEX). In the future, EmN guarantees energy efficiency, optimal Power Usage Effectiveness (PUE), and minimizing CO2 emissions (CO2 footprint).

The analysis of modern literature highlights demonstrated a trend in the development of heterogeneous IPv4 and IPv6 networks (heterogeneous networks), which include sensor networks and the routes of IoT (e.g., NB-IoT, LTE-CatM, LoRa WAN, 6LoWPAN, EnOcean), DSL, ATM, MPLS, Wi-Fi-6, WLANp, VLN, LiFi as well as hierarchical cells 5G and Beyond combined with SpaceX/ Starlink and radio relay areas.

When distinguishing the categories of OoS, QoE, and the introduction of a specific quality parameter "Q" by the method of expert assessments, we consider it necessary to determine the parameter of network security (e.g., as the intrusion probability, the percentage of intrusion detection and intrusion prevention, etc.).

Contents

Fault Identification in Linear Dynamic Systems by the Method of Locally Optimal Separate Estimation

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Abstract. In this article, the synthesis of two-stage structure recursive filter is carried out. The filter is resistant to unknown disturbances and is able to simultaneously evaluate both the state of the system and the malfunction has arisen in it. The presented synthesis method is based on the assumption that there is no a priori information about the dynamics of operating faults and disturbances. The provided synthesis method is based on assumption of the lack prior data about fault dynamics and perturbations. In this case, it is assumed that faults affect both the state of the system and the output variables, and disturbances affect only the state variables. Synthesis of the recursive filter was made in two options. In the first case, it was assumed that the distribution matrix of faults in the observation channel is a full rank matrix, then the result obtained was generalized to the case of an arbitrary rank matrix. The proposed filters are locally optimal in the sense of forming separate unbiased fault estimates and states with minimal variance. For these purposes, a matrix version of the Lagrange multiplier method was used. The operability of the considered method was tested on the example of an aircraft landing system. A comparative analysis of the qualitative variables of the proposed filter with the corresponding variables of the standard Kalman filter has been carried out. Solving this task is very important to improving the stability of operation and reliability of different communication equipment in the emerging networks, both local and global, both fixed and wireless.

Keywords: Decomposition · Kalman filter · Separate estimation · Lagrange multiplier method · Two-cascade estimation algorithm

1 Introduction

The modern state of telecommunication technologies can be characterized by the rapid acceleration of the network convergence processes, which represents mutual penetration of networks for different purposes based on the use of common components and the

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unification of functionality. The result of such convergence is the formation of overly complex physical systems. In turn, the development of telecommunications has reached a level at which qualitative changes in approaches to the construction of telecommunication networks must inevitably begin, while the quality of the functioning of networks, their reliability and safety always stay on the cutting edge of technologies.

In practice, there are often cases when the dynamics of complex physical systems will experience sudden changes. This, as a rule, leads to a deterioration in their quality indicators. In general, such changes can be classified as malfunctions or failures. Faults manifest themselves in the form of deviations from the regulated norms, and failures - in the form of an abnormal development of the process, due to a sharp change in the parameters of the system or its structure. In this regard, the system may become unable to perform the task assigned to it. To maintain the stable functionality of the system, the basic provisions of the fault-tolerant control theory are often used, based on a very simple idea - compensation for the influence of faults due to hard-ware-architectural or functional redundancy [1]. According to the well-known distribution theorem, strictly proven only for linear systems, the general problem of fault-tolerant control can be divided into two relatively independently solved problems - the problem of the state system estimation and the control problem using the obtained estimation results. In this work, attention is focused exclusively on the estimation problem associated with the detection of faults and their recognition by applying appropriate model-based methods. Recently, several basic approaches to solving this problem have been developed, for example, the method of parity relations, the detecting filters method, the method of observers with uncertain inputs, the generalized likelihood ratio, etc. Their characteristic features were considered in a number of review papers [2–7]. Several monographs and manuals have been published devoted to certain aspects of fault diagnostics in linear dynamic systems [1, 7, 8], and applied aspects were partially considered in works [7, 9]. To date, de facto, two concepts have already been formed regarding the solution of problems of estimating the state of linear systems in the presence of faults and uncontrolled disturbances. The first one is based on the idea of expanding the state vector of a nominal system by introducing an additional unknown vector input into its mathematical model, associated with the influence of existing faults and disturbances. However, this concept provides for the presence of an a priori given model of an unknown input. The optimal solution of the estimation problem is guaranteed by the extended Kalman filter, and with a large number of faults and disturbances taken into account, the dimension of the extended Kalman filter becomes much larger than the dimension of the nominal system. In order to save computational resources, Friedland [10] suggested approximating the extended Kalman filter by a parallel autonomously operating cascade structure of lower dimension, which turned out to be only quasi-optimal in terms of equivalence to the extended Kalman filter outputs. The application of the basic provisions of work [10] to the stochastic type of faults and disturbances encountered difficulties of an exclusively practical nature [11–13]. Today, the main efforts are aimed at finding methods for approximating the extended Kalman filter, which combine acceptable accuracy with fairly simple (for practical applications) restrictions [14, 15]. For example, for this purpose, an adaptive version of the two-stage Friedland filter was developed in [16] and its stability was analyzed [17].

An alternative concept is based on the assumption of complete absence of a priori information regarding the dynamic properties of unknown inputs. Kitanidis [18] was the first to start solving this problem in order to obtain linear unbiased estimators with minimal generalized variance by introducing constraints that were imposed on the structure of the system under study. In [20], the authors generalized the results of [18], applying a parametric approach to obtain optimal estimates. A little later, in [21], an optimal filter with a minimum dispersion was obtained, which took into account the problem of degradation of the accuracy characteristics inherent in Kitanidis filters. In [22], the problem of detecting faults and their localization was solved using a geometric approach, while generating difference signals with directional properties.

In the present work, methods of locally optimal separate filtering solve the problem of fault diagnostics in linear dynamic systems in the presence of perturbations of an indefinite structure. The study is based on the main provisions of [18] in order to reduce the restrictions that contribute to the divergence of the filtration process.

2 Problem Statement

Let us assume that the model of a system with accompanying faults and disturbances can be described by a system of equations:

$$\boldsymbol{s}(k+1) = \boldsymbol{\Sigma}(k+1,k)\boldsymbol{s}(k) + \boldsymbol{\Gamma}(k+1,k)\boldsymbol{u}(k) + \boldsymbol{\Psi}(k+1,k)\boldsymbol{f}(k) + \boldsymbol{\Omega}(k+1,k)\boldsymbol{d}(k) + \boldsymbol{w}(k) \tag{1}$$

$$\boldsymbol{y}(k) = \boldsymbol{H}(k)\boldsymbol{s}(k) + \boldsymbol{F}(k)\boldsymbol{f}(k) + \boldsymbol{v}(k) \tag{2}$$

where $\boldsymbol{s}(k) \in \mathcal{R}^n$– is the system state vector, $\boldsymbol{y}(k) \in \mathcal{R}^m$– is the observation vector, $\boldsymbol{u}(k) \in \mathcal{R}^r$– is the precisely known input action vector, $\boldsymbol{f}(k) \in \mathcal{R}^p$– is the additively acting fault vector, and $\boldsymbol{d}(k) \in \mathcal{R}^q$ – is the perturbation vector. White noise sequences $\boldsymbol{w}(k)$, $\boldsymbol{v}(k)$ are of Gaussian White noise, not correlated, have zero means and given covariance matrices, $\boldsymbol{Q}(k) \geq 0$, $\boldsymbol{R}(k) \geq 0$, respectively. A priori, it is assumed that the structure of the perturbation vector $\boldsymbol{d}(k)$ is indefinite, and may not even have a probabilistic description, and for it to be isolated from the state system vector, a decomposition procedure must be performed, which requires a number of additional restrictions, namely:

a) $[\boldsymbol{H}(k),\ \boldsymbol{\Sigma}(k+1,k)]$ – renewable pair; b) $n > m \geq p+q$; c) $rank[\boldsymbol{F}(k)] = p$;

$$\text{d) } rank[\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)] = rank[\boldsymbol{\Omega}(k,k-1)] = q. \tag{3}$$

He assumes that the system matrices $\boldsymbol{\Sigma}(k+1,k)$, $\boldsymbol{\Gamma}(k+1,k)$, $\boldsymbol{\Psi}(k+1,k)$, $\boldsymbol{\Omega}(k+1,k)$, $\boldsymbol{H}(k)$ and $\boldsymbol{F}(k)$ are known and have the corresponding dimensions. The initial system state $\boldsymbol{s}(0)$ is a Gaussian random variable, which is not correlated with noise processes $\boldsymbol{w}(k)$, $\boldsymbol{v}(k)$, has a given vector of average values $\mathcal{M}\{\boldsymbol{s}(0)\} = \bar{\boldsymbol{s}}_0$ and the covariance matrix $\mathcal{M}\{[\boldsymbol{s}(0)-\bar{\boldsymbol{s}}_0]\}[\boldsymbol{s}(0)-\bar{\boldsymbol{s}}_0]^T = \boldsymbol{P}_s(0)$. Here the symbol $\mathcal{M}\{\cdot\}$ will mean mathematical expectation. Taking into account the Eq. (1)–(2), it is easy to see that faults simultaneously affect both the system state and the output variables, and the perturbation affects only the system state. Taking into account the type of the introduced restrictions and relying on the fundamental type results of [18, 19], it can be argued that the conditions for dividing the resulting filter into two components are satisfied. The first of them evaluates the system state vector, while ignoring the influence of disturbances, and the second, for the same conditions, estimates only mal-functions. For a given split filter structure, the following standard relations are valid [19]:

$$\hat{\boldsymbol{s}}\left({}^{k}/_{k}\right) = \hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right) + \boldsymbol{K}_s(k)\left[\boldsymbol{y}(k) - \boldsymbol{H}(k)\hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right)\right] \tag{4}$$

$$\hat{\boldsymbol{s}}\left({}^{k}/_{k}\right) = \hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right) + \boldsymbol{K}_s(k)\left[\boldsymbol{y}(k) - \boldsymbol{H}(k)\hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right)\right] \tag{5}$$

$$\hat{\boldsymbol{s}}\left({}^{k}/_{k}\right) = \hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right) + \boldsymbol{K}_s(k)\left[\boldsymbol{y}(k) - \boldsymbol{H}(k)\hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right)\right] \tag{6}$$

where (6) describes the unifying extrapolator function. Thus, the task of synthesis is reduced to the choice of such values of the transmission matrices of separated filters $\boldsymbol{K}_s(k) \in \mathcal{R}^{n\times m}$ and $\boldsymbol{K}_f(k) \in \mathcal{R}^{p\times m}$, that would meet the selected quality criteria:

– absence of shifts in estimates of state vector $\hat{\boldsymbol{s}}\left({}^{k}/_{k}\right)$ and faults $\hat{\boldsymbol{f}}\left({}^{k}/_{k}\right)$;

$$\mathcal{M}\{\tilde{\boldsymbol{s}}(k)\} \triangleq \mathcal{M}\left\{\boldsymbol{s}(k) - \hat{\boldsymbol{s}}\left({}^{k}/_{k}\right)\right\} = 0;\ \mathcal{M}\left\{\tilde{\boldsymbol{f}}(k)\right\} \triangleq \mathcal{M}\left\{[\boldsymbol{f}(k) - \hat{\boldsymbol{f}}\left({}^{k}/_{k}\right)]\right\} = 0 \tag{7}$$

– minimal mean squared errors in estimates $\hat{\boldsymbol{f}}\left({}^{k}/_{k}\right)$;

– minimal trace of the error covariance matrix in the estimates of the state vector $\hat{\boldsymbol{s}}\left({}^{k}/_{k}\right)$, subject to the validity of restrictions (7), that is

$$\min\ tr\mathcal{M}\left\{\tilde{\boldsymbol{s}}(k)\tilde{\boldsymbol{s}}^T(k)\right\} = \min\ tr\left[\boldsymbol{P}_s\left({}^{k}/_{k}\right)\right]. \tag{8}$$

3 Synthesis of Locally Optimal Filters of Separate Estimation

Let us apply the filter (4)–(6) to systems t (1)–(2) and determine the residual of observations $\boldsymbol{r}(k) \triangleq \boldsymbol{y}(k) - \boldsymbol{H}(k)\hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right)$ subject to constraint (3 c). It is easy to show that the difference $\boldsymbol{r}(k)$ can be reduced to the form:

$$\boldsymbol{r}(k) \triangleq \boldsymbol{y}(k) - \boldsymbol{H}(k)\hat{\boldsymbol{s}}\left({}^{k}/_{k-1}\right) = \boldsymbol{F}(k)\boldsymbol{f}(k) + \boldsymbol{H}(k)\boldsymbol{\Psi}(k, k-1)\boldsymbol{d}(k-1) + \boldsymbol{e}(k); \tag{9}$$

where

$$\boldsymbol{e}(k) = \boldsymbol{H}(k)\tilde{\boldsymbol{s}}^*\left({}^{k}/_{k-1}\right) + \boldsymbol{v}(k); \tag{10}$$

$$\tilde{\boldsymbol{s}}^*\left({}^{k}/_{k-1}\right) = \boldsymbol{\Sigma}(k, k-1)\tilde{\boldsymbol{s}}(k-1) + \boldsymbol{\Psi}(k, k-1)\tilde{\boldsymbol{f}}(k-1) + \boldsymbol{w}(k-1), \tag{11}$$

and expressions for estimation errors should be presented as:

$$\tilde{\boldsymbol{f}}(k) \triangleq \left[\boldsymbol{f}(k) - \hat{\boldsymbol{f}}\left({}^{k}/_{k}\right)\right] = \left[\boldsymbol{I} - \boldsymbol{K}_f(k)\boldsymbol{F}(k)\right]\boldsymbol{f}(k) - \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k, k-1)\boldsymbol{d}(k-1) - \boldsymbol{K}_f(k)\boldsymbol{e}(k); \tag{12}$$

$$\tilde{s}(k) \triangleq \left[s(k) - \hat{s}\left({}^{k}/_{k}\right)\right] = [\boldsymbol{I} - \boldsymbol{K}_s(k)\boldsymbol{H}(k)]\tilde{\boldsymbol{s}}^*\left({}^{k}/_{k-1}\right) - \boldsymbol{K}_s(k)\boldsymbol{F}(k)\boldsymbol{f}(k) - \\ - [\boldsymbol{K}_s(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1) - \boldsymbol{\Omega}(k,k-1)]\boldsymbol{d}(k-1) - \boldsymbol{K}_s(k)\boldsymbol{v}(k). \tag{13}$$

First, consider the constraints that must be met in order to obtain unbiased estimates of the vectors $\hat{\boldsymbol{s}}\left({}^{k}/_{k}\right)$ and $\hat{\boldsymbol{f}}\left({}^{k}/_{k}\right)$ by criterion (7), and the estimation process itself will be considered in the text below. In accordance with the above requirements, the following algebraic restrictions must be imposed on the matrices $\boldsymbol{K}_s(k)$ and $\boldsymbol{K}_f(k)$:

$$\boldsymbol{K}_f(k)\boldsymbol{G}(k) = \boldsymbol{\Phi}(k), \ \ \boldsymbol{K}_s(k)\boldsymbol{G}(k) = \boldsymbol{Z}(k), \tag{14}$$

where $$\boldsymbol{G}(k) = [\boldsymbol{F}(k) \ \ \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)]; \ \boldsymbol{\Phi}(k) = \left[\boldsymbol{I}_p \ \ \boldsymbol{0}\right]; \ \boldsymbol{Z}(k) = [\boldsymbol{0} \ \ \boldsymbol{\Omega}(k,k-1)]. \tag{15}$$

This is easy to verify if you perform the following steps. For example, we restrict ourselves to Eq. (12). In order to avoid shifts, in (12), we equate to zero the expression: $\left[\boldsymbol{I} - \boldsymbol{K}_f(k)\boldsymbol{F}(k)\right]\boldsymbol{f}(k) - \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)\boldsymbol{d}(k-1) = \boldsymbol{0}$.

A series of further, simple calculations gives the desired result:

$$\boldsymbol{K}_f(k)\boldsymbol{F}(k)\boldsymbol{f}(k) + \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)\boldsymbol{d}(k-1) = \boldsymbol{I}_p\boldsymbol{f}(k);$$
$$\left[\boldsymbol{K}_f(k)\boldsymbol{F}(k) \ \ \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)\right]\begin{bmatrix} f(k) \\ \boldsymbol{d}(k-1) \end{bmatrix} = \left[\boldsymbol{I}_p \ \ \boldsymbol{0}\right]\begin{bmatrix} f(k) \\ \boldsymbol{d}(k-1) \end{bmatrix};$$
$$\boldsymbol{K}_f(k)[\boldsymbol{F}(k) \ \ \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)]\begin{bmatrix} f(k) \\ \boldsymbol{d}(k-1) \end{bmatrix} = \left[\boldsymbol{I}_p \ \ \boldsymbol{0}\right]\begin{bmatrix} f(k) \\ \boldsymbol{d}(k-1) \end{bmatrix};$$
$$\boldsymbol{G}(k) \triangleq [\boldsymbol{F}(k) \ \ \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)]; \quad \boldsymbol{\Phi}(k) \triangleq \left[\boldsymbol{I}_p \ \ \boldsymbol{0}\right].$$

Similar actions using (13) allow us to calculate the matrix $\boldsymbol{Z}(k) = [\boldsymbol{0} \ \ \boldsymbol{\Omega}(k,k-1)]$.

If assumptions b, d from (3) are valid, and the matrix is a full rank matrix, then a necessary and sufficient condition for the existence of unbiased estimates and is the requirement that the matrix be a full rank matrix by the columns, that is:

$$rank[\boldsymbol{G}(k)] = rank[\boldsymbol{F}(k) \quad \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)] = p + q. \tag{16}$$

To confirm this, we first rewrite Eq. (14) in the vector form $\begin{bmatrix} \boldsymbol{K}_f(k) \\ \boldsymbol{K}_s(k) \end{bmatrix}\boldsymbol{G}(k) = \begin{bmatrix} \boldsymbol{\Phi}(k) \\ \boldsymbol{Z}(k) \end{bmatrix}$. This inhomogeneous matrix equation has a single solution with respect to $\begin{bmatrix} \boldsymbol{K}_f(k) \\ \boldsymbol{K}_s(k) \end{bmatrix}$, if the augmented matrix (due to the inclusion of the right hand side) has the rank of the matrix $\boldsymbol{G}(k)$ [20], that is $rank\begin{bmatrix} \boldsymbol{\Phi}(k) \\ \boldsymbol{Z}(k) \\ \boldsymbol{G}(k) \end{bmatrix} = rank[\boldsymbol{G}(k)]$.

Further, we will expand the matrices $\begin{bmatrix} \boldsymbol{\Phi}(k) \\ \boldsymbol{Z}(k) \end{bmatrix}$ in accordance to the expression (15):

$$rank\begin{bmatrix} \boldsymbol{I}_p & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\Omega}(k,k-1) \\ \boldsymbol{F}(k) & \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1) \end{bmatrix} = rank[\boldsymbol{F}(k) \quad \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)]. \tag{17}$$

The matrix that is on the left side of the equals sign has rank $p + q$. This is easy to check using assumptions (3 b, d), in addition, it is assumed that the rank of the matrix is $\boldsymbol{F}(k)$ equal to p. Since faults and disturbances are independent processes, the requirement (16) remains the condition for the absence of shifts in the estimates $\hat{\boldsymbol{f}}\left(k/k\right)$ and $\hat{\boldsymbol{s}}\left(k/k\right)$.

The Optimal Faults Estimation. Let's perform the transformation in (9) bringing it to the form:

$$\boldsymbol{r}(k) = \boldsymbol{G}(k)\begin{bmatrix} \boldsymbol{f}(k) \\ \boldsymbol{d}(k-1) \end{bmatrix} + \boldsymbol{e}(k) \tag{18}$$

where $\boldsymbol{e}(k)$ in accordance with (10) denoted as $\boldsymbol{e}(k) = \boldsymbol{H}(k)\widetilde{\boldsymbol{s}}^{*}\left(k/_{k-1}\right) + \boldsymbol{v}(k)$. It is easy to see that the process $\boldsymbol{e}(k)$ doesn't belong to random processes with unit variance. For this reason, it doesn't meet the conditions of the Markov theorem and normality inherent in the innovation process [24], and the use of the least squares method will not guarantee the minimum value of the estimation errors dispersion. However, the extrapolation error covariance matrix has the form

$$\boldsymbol{W}(k) = \mathcal{M}\left\{\boldsymbol{e}(k)\boldsymbol{e}^{T}(k)\right\} = \boldsymbol{H}(k)\overline{\boldsymbol{P}}_{s}\left(k/_{k-1}\right)\boldsymbol{H}^{T}(k) + \boldsymbol{R}(k), \tag{19}$$

where $\overline{P}_S\left(k/_{k-1}\right) \cong \mathcal{M}\left[\tilde{s}^{*}\left(k/_{k-1}\right)\tilde{s}^{*T}\left(k/_{k-1}\right)\right]$. Despite this, it seems possible to obtain the minimum value of the dispersion, if we use the weighted least squares method, while introducing the normalization matrix weight coefficient $\boldsymbol{W}^{-1}(k)$. To do this, it is necessary to assume that the extrapolation error estimate $\widetilde{\boldsymbol{s}}^{*}\left(k/_{k-1}\right)$ is unbiased, the matrix $\boldsymbol{G}(k)$ has a full rank by columns, and $\boldsymbol{W}(k)$ is positively denoted, then an unbiased fault estimate with minimum variance is guaranteed by the transfer matrix $\boldsymbol{K}_{f}^{*}(k)$ that is given by the expression

$$\boldsymbol{K}_{f}^{*}(k) = \boldsymbol{\Phi}(k)\boldsymbol{G}^{*}(k), \quad \text{where } \boldsymbol{G}^{*}(\mathrm{k}) = \left[\boldsymbol{G}^{\mathrm{T}}(\mathrm{k})\boldsymbol{W}^{-1}(\mathrm{k})\boldsymbol{G}(\mathrm{k})\right]^{-1}\boldsymbol{G}^{\mathrm{T}}(\mathrm{k})\boldsymbol{W}^{-1}(\mathrm{k}). \tag{20}$$

Moreover, if the matrix $\boldsymbol{W}(k)$ is positively denoted and has an inverse, then it is always possible to find such the matrix $\boldsymbol{\Theta}(k) \in \mathcal{R}^{m\times m}$ that is related to the matrix $\boldsymbol{W}(k)$ by the relation $\boldsymbol{\Theta}(k)\boldsymbol{\Theta}^{T}(k) = \boldsymbol{W}(k)$ [22]. Then formula (18) can be written as

$$\boldsymbol{\Theta}^{-1}(k)\boldsymbol{r}(k) = \boldsymbol{\Theta}^{-1}(k)\boldsymbol{G}(k)\begin{bmatrix} \boldsymbol{f}(k) \\ \boldsymbol{d}(k-1) \end{bmatrix} + \boldsymbol{\Theta}^{-1}(k)\boldsymbol{e}(k). \tag{21}$$

Since the matrix $\boldsymbol{G}(k)$ s the full column rank matrix (that is equal to $p + q$) by assumption, then the matrix $\boldsymbol{G}^{T}(k)\boldsymbol{\Theta}^{-1}(k)\boldsymbol{G}(k)$ can be inverse. For this reason, the solution obtained by the weighted least squares method for (8) is equivalent to the least squares solution for (21)

$$\boldsymbol{f}^{*}\left(k/_{k}\right) = \boldsymbol{\Phi}(k)\left[\boldsymbol{G}^{T}(k)\boldsymbol{W}^{-1}(k)\boldsymbol{G}(k)\right]^{-1}\boldsymbol{G}^{T}(k)\boldsymbol{W}^{-1}(k)\boldsymbol{r}(k). \tag{22}$$

Then the quantity $\boldsymbol{\Theta}^{-1}(k)\boldsymbol{e}(k)$ can be considered as such that it has unit variance and satisfies the Markov conditions and is Gaussian. After all, (22) is an unbiased estimator with a minimum variance. In this case, the fault estimation error can be represented as

$$\widetilde{\boldsymbol{f}}^{*}(k) = -\boldsymbol{K}_{f}^{*}(k)\boldsymbol{e}(k), \tag{23}$$

and using formula (23), one can calculate the covariance matrix of filtering errors in the form:

$$\boldsymbol{P}^{*}{}_{f}\left({}^{k}\!/_{k}\right) \triangleq \mathcal{M}\left\{\boldsymbol{f}^{*}(k)\boldsymbol{f}^{*T}(k)\right\} = \boldsymbol{K}^{*}{}_{f}(k)\boldsymbol{W}(k)\boldsymbol{K}^{*T}{}_{f}(k) = \boldsymbol{\Phi}(k)\left[\boldsymbol{G}^{T}(k)\boldsymbol{W}^{-1}(k)\boldsymbol{G}(k)\right]^{-1}\boldsymbol{\Phi}^{T}(k). \tag{24}$$

The Optimal State Vector Estimation. In this section, we consider the procedure for correctly choosing the matrix filter gain $\boldsymbol{K}_{s}^{*}(k)$ that minimizes the trace of the covariance matrix of filtering errors in the presence of constraints $\boldsymbol{K}_{s}(k)\boldsymbol{G}(k) = \boldsymbol{Z}(k)$. This guarantees the absence of shifts in the estimates of the system state vector $\boldsymbol{s}^{*}\left({}^{k}\!/_{k}\right)$. If the matrix $\boldsymbol{G}^{T}(k)\boldsymbol{W}^{-1}(k)\boldsymbol{G}(k)$ is not singular, then the transfer matrix of the filter that generates the estimate $\boldsymbol{s}^{*}\left({}^{k}\!/_{k}\right)$ with the minimum value of the covariance matrix trace of filtering errors $\boldsymbol{P}_{s}^{*}\left({}^{k}\!/_{k}\right)$ is defined as

$$\boldsymbol{K}_{s}^{*}(k) = \overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right)\boldsymbol{H}^{T}(k)\boldsymbol{W}^{-1}(k)\left[\boldsymbol{I} - \boldsymbol{G}(k)\boldsymbol{G}^{*}(k)\right] + \boldsymbol{Z}(k)\boldsymbol{G}^{*}(k) \tag{25}$$

on condition of restriction observance (14).

To test this assumption turning to formulas (13)–(14), we calculate the filtering errors covariance matrix by the expression:

$$\begin{aligned}\boldsymbol{P}_{s}\left({}^{k}\!/_{k}\right) \triangleq \mathcal{M}\left\{\widetilde{s}(k)\widetilde{\boldsymbol{s}}^{T}(k)\right\} &= [\boldsymbol{I} - \boldsymbol{K}_{s}(k)\boldsymbol{H}(k)]\overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right)[\boldsymbol{I} - \boldsymbol{K}_{s}(k)\boldsymbol{H}(k)]^{T} + \boldsymbol{K}_{s}(k)\boldsymbol{R}(k)\boldsymbol{K}_{s}^{T}(k) = \\ &= \boldsymbol{K}_{s}(k)\boldsymbol{W}(k)\boldsymbol{K}_{s}^{T}(k) - 2\overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right)\boldsymbol{H}^{T}(k)\boldsymbol{K}_{s}^{T}(k) + \overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right).\end{aligned} \tag{26}$$

In the future, to minimize the trace of this matrix, we will apply the variational methods, for example, the method of Lagrange vector multipliers. To do this, we introduce an auxiliary function, the so-called Lagrange matrix function [23]

$$\begin{aligned}\boldsymbol{\varphi}_{L}(k) = &tr\left\{\boldsymbol{K}_{s}(k)\boldsymbol{W}(k)\boldsymbol{K}_{s}^{T}(k) - 2\overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right)\boldsymbol{H}^{T}(k)\boldsymbol{K}_{s}^{T}(k) + \overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right)\right\} - \\ &- 2tr\left\{[\boldsymbol{K}_{s}(k)\boldsymbol{G}(k) - \boldsymbol{Z}(k)]\boldsymbol{\Lambda}^{T}(k)\right\}\end{aligned} \tag{27}$$

where $\boldsymbol{\Lambda}(k)$– is the matrix of Lagrange multipliers. Here, the factor 2 is chosen purely for convenience, since it doesn't affect the minimization process in any way. If we calculate the gradient of this function with respect to $\boldsymbol{K}_{s}(k)$ and equate it to zero, then the minimum condition will

$$\boldsymbol{W}(k)\boldsymbol{K}_{s}^{T}(k) - \boldsymbol{H}(k)\overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right) - \boldsymbol{G}(k)\boldsymbol{\Lambda}^{T}(k) = \boldsymbol{0}. \tag{28}$$

Now let's combine Eqs. (14) and (28) into a system of vector equations

$$\begin{bmatrix}\boldsymbol{W}(k) & -\boldsymbol{G}(k)\\ \boldsymbol{G}^{T}(k) & 0\end{bmatrix}\begin{bmatrix}\boldsymbol{K}_{s}^{T}(k)\\ \boldsymbol{\Lambda}^{T}(k)\end{bmatrix} = \begin{bmatrix}\boldsymbol{H}(k)\overline{\boldsymbol{P}}_{s}\left({}^{k}\!/_{k-1}\right)\\ \boldsymbol{Z}^{T}(k)\end{bmatrix}. \tag{29}$$

System (29) has a single solution with respect to $\begin{bmatrix} \boldsymbol{K}_s^T(k) \\ \boldsymbol{\Lambda}^T(k) \end{bmatrix}$ if the block matrix $\begin{bmatrix} \boldsymbol{W}(k) & -\boldsymbol{G}(k) \\ \boldsymbol{G}^T(k) & 0 \end{bmatrix}$ is not singular – it has an inverse. Turning to [25], it is easy to make sure that the condition for the existence of the inverse block matrix is the non-singularity of the matrix $\boldsymbol{G}^T(k)\boldsymbol{W}^{-1}(k)\boldsymbol{G}(k)$. This means that (29) has a single solution.

In a standard way according to formulas (4)–(5) and (11), the filter is corrected in the time domain:

$$\begin{aligned}
&\overline{\boldsymbol{P}}_S\left(k/_{k-1}\right) \triangleq \mathcal{M}\left\{\boldsymbol{s}^*\left(k/_{k-1}\right)\boldsymbol{s}^{*T}\left(k/_{k-1}\right)\right\} = \\
&= \begin{bmatrix} \boldsymbol{\Sigma}(k,k-1) & \boldsymbol{\Psi}(k,k-1) \end{bmatrix} \begin{bmatrix} \boldsymbol{P}_S^*\left(k-1/_{k-1}\right) & \boldsymbol{P}_{Sf}^*\left(k-1/_{k-1}\right) \\ \boldsymbol{P}_{fS}^*\left(k-1/_{k-1}\right) & \boldsymbol{P}_f^*\left(k-1/_{k-1}\right) \end{bmatrix} \begin{bmatrix} \boldsymbol{\Sigma}^T(k,k-1) \\ \boldsymbol{\Psi}^T(k,k-1) \end{bmatrix} + \boldsymbol{Q}(k-1); \qquad (30)\\
&\boldsymbol{P}_{sf}^*\left(k/_k\right) \triangleq \mathcal{M}\left\{\boldsymbol{s}^*\left(k/_k\right)\boldsymbol{f}^*\left(k/_k\right)^T\right\} = \\
&= \boldsymbol{K}^*_s(k)\,\boldsymbol{R}(k)\,\boldsymbol{K}^{*T}_f(k) - \left[\boldsymbol{I}-\boldsymbol{K}^*_s(k)\boldsymbol{H}(k)\right]\overline{\boldsymbol{P}}_S\left(k/_{k-1}\right)\boldsymbol{H}^T(k)\,\boldsymbol{K}^{*T}_f(k).
\end{aligned}$$

4 Generalization of the Locally Optimal Estimation for the Case of the Arbitrary Rank Distribution Matrix of Faults

In this section, we consider the case when the distribution matrix of faults in the observation subsystem can have an arbitrary rank in the range from one to p, that is, $0 < rank[\boldsymbol{F}(k)] < p$. The extension of the filter functionality is achieved by introducing additional restrictions that are imposed on the system matrices of Eqs. (1)–(2), and optimization is performed on a space of lower dimension, since not all modes can be restored from the observation results. Moreover, non-renewable modes must remain in the persistent modes class, otherwise the filter cannot be implemented in practice. Since the vast majority of mathematical calculations are identical to those given in the previous subsection, the presentation of the material will be brief with references to individual literary sources. If we substitute formulas (10)–(11) into Eqs. (12), then the estimate error fault will be presented as:

$$\begin{aligned}
\widetilde{\boldsymbol{f}}(k) &= \left[\boldsymbol{I}-\boldsymbol{K}_f(k)\boldsymbol{F}(k)\right]\boldsymbol{f}(k) - \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)\boldsymbol{d}(k-1) - \boldsymbol{K}_f(k)\left[\boldsymbol{H}(k)\widetilde{\boldsymbol{s}}^*\left(k/_{k-1}\right)+\boldsymbol{v}(k)\right] = \\
&= -\boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Psi}(k,k-1)\widetilde{\boldsymbol{f}}(k-1) - \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Sigma}(k,k-1)\widetilde{\boldsymbol{s}}(k-1) + \\
&+ \left[\boldsymbol{I}-\boldsymbol{K}_f(k)\boldsymbol{F}(k)\right]\boldsymbol{f}(k) - \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)\boldsymbol{d}(k-1) - \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{w}(k-1) - \boldsymbol{K}_f(k)\boldsymbol{v}(k).
\end{aligned} \qquad (31)$$

Next, we introduce a series of notation, provided there is no shift $\mathcal{M}\{\widetilde{\boldsymbol{s}}(k-1)\} = \boldsymbol{0}$ in the previous estimate:

$$\boldsymbol{\Phi}(k) \triangleq \boldsymbol{K}_f(k)\boldsymbol{F}(k) = \boldsymbol{I}_p - \boldsymbol{\Xi}(k), \qquad (32)$$

where $\boldsymbol{\Xi}(k) = \boldsymbol{I} - \boldsymbol{F}^{\#}(k)\boldsymbol{F}(k)$; $\boldsymbol{G}_f(k) \triangleq \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Psi}(k,k-1)$;

$\boldsymbol{G}_d(k) \triangleq \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)$; # – symbol denotes the Moore-Penrose pseudo-inversion operation.

Using the method of work [26], we expand the mathematical expectation of the fault estimation error into a functional matrix series:

$$\begin{aligned}&\mathcal{M}\{\widetilde{\boldsymbol{f}}(k)\} = \boldsymbol{\Xi}(k)\boldsymbol{f}(k) - \boldsymbol{G}_f(k)\boldsymbol{\Xi}(k-1)\boldsymbol{f}(k-1)+\\&+\boldsymbol{G}_f(k)\left[\boldsymbol{G}_f(k-1)\boldsymbol{\Xi}(k-2)\right]\boldsymbol{f}(k-2)+\ldots+(-1)^k\boldsymbol{G}_f(k)\times\ldots\times\boldsymbol{G}_f(2)\left[\boldsymbol{G}_f(1)\boldsymbol{\Xi}(0)\right]\boldsymbol{f}(0)-\\&-\boldsymbol{G}_d(k)\boldsymbol{d}(k-1)+\boldsymbol{G}_f(k)\boldsymbol{G}_d(k-1)\boldsymbol{d}(k-2)+\ldots+(-1)^k\boldsymbol{G}_f(k)\times\ldots\times\boldsymbol{G}_f(1)\boldsymbol{G}_d(1)\boldsymbol{d}(0),\end{aligned} \tag{33}$$

and confine ourselves to the first-order approximation, putting all the values $\boldsymbol{G}_f(i)\boldsymbol{\Xi}(i-1)=0;\ \ \boldsymbol{G}_d(i)=0$ для $i=1,\ldots,k$.

This will mean that the previous values of the fault vectors do not influence the cur-rent value of the mathematical expectation. Then we get $\mathcal{M}\{\widetilde{\boldsymbol{f}}(k)\} = \boldsymbol{\Xi}(k)\boldsymbol{f}(k)$. By analogy with (14)–(15), in order for the fault estimate to have no shift, the transfer matrix must satisfy the imposed constraint:

$$\boldsymbol{K}_f(k)\boldsymbol{F}(k) = \boldsymbol{\Phi}(k);\quad \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1) = \boldsymbol{0};\quad \boldsymbol{K}_f(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1) = \boldsymbol{0}. \tag{34}$$

In what follows, the system of Eqs. (34) will be represented in matrix form:

$$\boldsymbol{K}_f(k)\overline{\boldsymbol{G}}(k) = \overline{\boldsymbol{\Phi}}(k), \tag{35}$$

where $\overline{\boldsymbol{G}}(k) = [\boldsymbol{H}(k)\quad \boldsymbol{H}(k)\boldsymbol{\Psi}(k,k-1)\quad \boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1)]$; $\overline{\boldsymbol{\Phi}}(k) = [\boldsymbol{\Phi}(k)\ \ \boldsymbol{0}\ \ \boldsymbol{0}]$.

Combining (35) with (32) allows us to reduce the transfer matrix $\boldsymbol{K}_f(k)$ to the form

$$\boldsymbol{K}_f^*(k) = \overline{\boldsymbol{\Phi}}(k)\overline{\boldsymbol{G}}^*(k);\quad \overline{\boldsymbol{G}}^*(k) = \left[\overline{\boldsymbol{G}}^T(k)\boldsymbol{W}^{-1}(k)\overline{\boldsymbol{G}}(k)\right]^{\#}\overline{\boldsymbol{G}}^T(k)\boldsymbol{W}^{-1}(k). \tag{36}$$

Consider the state vector estimation error:

$$\begin{aligned}&\widetilde{\boldsymbol{s}}(k) = [\boldsymbol{I} - \boldsymbol{K}_s(k)\boldsymbol{H}(k)]\widetilde{\boldsymbol{s}}^*\left(k/_{k-1}\right) - \boldsymbol{K}_s(k)\boldsymbol{F}(k)\boldsymbol{f}(k)-\\&-[\boldsymbol{K}_s(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1) - \boldsymbol{\Omega}(k,k-1)]\boldsymbol{d}(k-1) - \boldsymbol{K}_s(k)\boldsymbol{v}(k) =\\&= [\boldsymbol{I} - \boldsymbol{K}_s(k)\boldsymbol{H}(k)]\boldsymbol{\Sigma}(k,k-1)\widetilde{\boldsymbol{s}}(k-1) + [\boldsymbol{I} - \boldsymbol{K}_s(k)\boldsymbol{H}(k)]\boldsymbol{\Psi}(k,k-1)\widetilde{\boldsymbol{f}}(k)-\\&-[\boldsymbol{K}_s(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1) - \boldsymbol{\Omega}(k,k-1)]\boldsymbol{d}(k-1) - \boldsymbol{K}_s(k)\boldsymbol{F}(k)\boldsymbol{f}(k)+\\&+[\boldsymbol{I} - \boldsymbol{K}_s(k)\boldsymbol{H}(k)]\boldsymbol{w}(k-1) - \boldsymbol{K}_s(k)\boldsymbol{v}(k).\end{aligned} \tag{37}$$

In order for the estimate of the camp vector to have no shifts, the matrix must satisfy the following introduced restriction:

$$\begin{aligned}&\boldsymbol{K}_s(k)\boldsymbol{F}(k) = \boldsymbol{0};\quad \boldsymbol{K}_s(k)\boldsymbol{H}(k)\boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1) = \boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1);\\&\boldsymbol{K}_s(k)\boldsymbol{H}(k)\boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1) = \boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1);\quad \boldsymbol{K}_s(k)\boldsymbol{H}(k)\boldsymbol{\Omega}(k,k-1) = \boldsymbol{\Omega}(k,k-1).\end{aligned} \tag{38}$$

In the combined form, the equivalent notation for (38) is

$$\boldsymbol{K}_s(k)\overline{\boldsymbol{G}}(k) = \overline{\boldsymbol{Z}}(k); \overline{\boldsymbol{Z}}(k) = [\boldsymbol{0}\quad \boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1)\quad \boldsymbol{\Omega}(k,k-1)]. \tag{39}$$

Table 1. Summary table of separate assessment formulas.

<table>
<tr><td colspan="2">Model of the process under study:
$s(k+1)=\boldsymbol{\Sigma}(k+1,k)s(k)+\boldsymbol{\Gamma}(k+1,k)u(k)+\boldsymbol{\Psi}(k+1,k)f(k)+\boldsymbol{\Omega}(k+1,k)d(k)+w(k)$;</td></tr>
<tr><td colspan="2">Observation channel model: $y(k)=H(k)s(k)+F(k)f(k)+v(k)$.</td></tr>
<tr><td colspan="2">Prior data:
1. $s(k)\in\mathcal{R}^n,\quad u(k)\in\mathcal{R}^r,\quad f(k)\in\mathcal{R}^p,\quad d(k)\in\mathcal{R}^q,\quad y(k)\in\mathcal{R}^m;$
2. $u(k)$ – well-known control input;
3. $\boldsymbol{\Sigma}(k+1,k),\ \boldsymbol{\Gamma}(k+1,k),\ \boldsymbol{\Psi}(k+1,k),(k),\ \boldsymbol{\Omega}(k+1,k),\ H(k),\ F(k)$ – given matrices;
4. $\mathcal{M}\{s(0)\}=\bar{s}_0;\quad \mathcal{M}\{w(k)\}=\mathcal{M}\{v(k)\}=\mathbf{0};\quad \mathcal{M}\left\{\left[s(0)-\bar{s}_0\right]\left[s(0)-\bar{s}_0\right]^T\right\}=P_s(0);$
$\mathcal{M}\left\{\left[w(k)w^T(j)\right]\right\}=Q(k)\delta(k-j);\ \mathcal{M}\left\{\left[v(k)v^T(j)\right]\right\}=R(k)\delta(k-j);$
$\mathcal{M}\left\{\left[s(0),w^T(k)\right]\right\}=\mathcal{M}\left\{\left[s(0),v^T(k)\right]\right\}=\mathcal{M}\left\{\left[w(k),v^T(j)\right]\right\}=\mathbf{0};$
5. Constraint: a) $\left[H(k),\ \boldsymbol{\Sigma}(k+1,k)\right]$ – observed pair; b) $n>m\geq p+q;$
c) $0<rank\left[F(k)\right]\leq p$; d) $rank\left[H(k)\boldsymbol{\Omega}(k,k-1)\right]=rank\left[\boldsymbol{\Omega}(k,k-1)\right]=q$.</td></tr>
<tr><td colspan="2">Fault evaluation</td></tr>
<tr><td colspan="2">$W(k)\triangleq H(k)\bar{P}_s\left(k/_{k-1}\right)H^T(k)+R(k)$;</td></tr>
<tr><td>$rank\left[F(k)\right]=p$</td><td>$0<rank\left[F(k)\right]<p$</td></tr>
<tr><td>$G(k)=\left[F(k)\ \ H(k)\boldsymbol{\Omega}(k,k-1)\right];$
$\boldsymbol{\Phi}(k)=\left[I_p\ \ \mathbf{0}\right];$
$G^*(k)=\left[G^T(k)W^{-1}(k)G(k)\right]^{-1}\times$
$\times G^T(k)W^{-1}(k);$
$K_f(k)=\boldsymbol{\Phi}(k)G^*(k).$</td><td>$\boldsymbol{\Xi}(k-1)=\left[I-F^{\#}(k-1)F(k-1)\right];$
$\bar{G}(k)=\begin{bmatrix}F(k)\ \ H(k)\boldsymbol{\Psi}(k,k-1)\boldsymbol{\Xi}(k-1)\times\\ \times H(k)\boldsymbol{\Omega}(k,k-1)\end{bmatrix};$
$\boldsymbol{\Phi}(k)=I_p-\boldsymbol{\Xi}(k);\ \bar{\boldsymbol{\Phi}}(k)=\left[\boldsymbol{\Phi}(k)\ \ \mathbf{0}\ \ \mathbf{0}\right];$
$\bar{G}^*(k)=\left[\bar{G}^T(k)W^{-1}(k)\bar{G}(k)\right]^{\#}\bar{G}^T(k)W^{-1}(k);$
$K_f(k)=\bar{\boldsymbol{\Phi}}(k)\bar{G}^*(k).$</td></tr>
</table>

(*continued*)

Table 1. (*continued*)

<table>
<tr><td colspan="2">$f\left(k/k\right)=K_f(k)\left[y(k)-H(k)\hat{s}\left(k/k-1\right)\right]; \quad P_f\left(k/k\right)=K_f(k)W(k)K^T{}_f(k).$</td></tr>
<tr><td colspan="2">System vector estimation</td></tr>
<tr><td>$rank\left[F(k)\right]=p;$</td><td>$0<rank\left[F(k)\right]<p$</td></tr>
<tr><td>$Z(k)=\left[0 \quad \Omega(k,k-1)\right];$
$K_s(k)=\overline{P}_s\left(k/k-1\right)H^T(k)W^{-1}(k)\times$
$\times\left[I-G(k)G^*(k)\right]+Z(k)G^*(k).$</td><td>$\overline{Z}(k)=\left[0 \quad \Psi(k,k-1)\Xi(k-1) \quad \Omega(k,k-1)\right];$
$K_s(k)=\overline{P}_s\left(k/k-1\right)H^T(k)W^{-1}(k)\left[I-\overline{G}(k)\overline{G}^*(k)\right]+$
$+\overline{Z}(k)\overline{G}^*(k);$</td></tr>
<tr><td colspan="2">$\hat{s}\left(k/k\right)=\hat{s}\left(k/k-1\right)+K_s(k)\left[y(k)-H(k)\hat{s}\left(k/k-1\right)\right];$
$P_s\left(k/k\right)=\left[I-K_s(k)H(k)\right]\overline{P}_s\left(k/k-1\right)\left[I-K_s(k)H(k)\right]^T+K_s(k)R(k)K^T{}_s(k);$
$P_{sf}{}^*\left(k/k\right)=-\left[I-K_s(k)H(k)\right]\overline{P}_s\left(k/k-1\right)H^T(k)K^T{}_f(k)+K_s(k)R(k)K^T{}_f(k).$</td></tr>
<tr><td colspan="2">Time Filter Correction :
$\hat{s}\left(k/k-1\right)=\Sigma(k,k-1)\hat{s}\left(k-1/k-1\right)+\Gamma(k,k-1)u(k-1)+\Psi(k,k-1)f\left(k-1/k-1\right);$
$\overline{P}_s\left(k/k-1\right)=\left[\Sigma(k,k-1) \quad \Psi(k,k-1)\right]\begin{bmatrix} P_s\left(k-1/k-1\right) & P_{sf}\left(k-1/k-1\right) \\ P_{fs}\left(k-1/k-1\right) & P_f\left(k-1/k-1\right)\end{bmatrix}\begin{bmatrix}\Sigma^T(k,k-1) \\ \Psi^T(k,k-1)\end{bmatrix}+Q(k-1).$</td></tr>
</table>

Taking into account the entries (10)–(11) and (37), it is now possible to calculate the error estimation covariance matrix of the state vector by the expression:

$$P_s\left({}^k/_k\right) \triangleq \mathcal{M}\left\{\widetilde{s}(k)\widetilde{s}^T(k)\right\} = [I - K_s(k)H(k)]\overline{P}_s\left({}^k/_{k-1}\right)[I - K_s(k)H(k)]^T +$$
$$+ K_s(k)R(k)K_s^T(k) = K_s(k)W(k)K_s^T(k) - 2\overline{P}_s\left({}^k/_{k-1}\right)H^T(k)K_s^T(k) + \overline{P}_s\left({}^k/_{k-1}\right). \tag{40}$$

Minimization of the trace $P_s\left({}^k/_k\right)$ is performed by the method of Lagrange multipliers. By analogy with (27)–(29) we get:

$$\begin{bmatrix} W(k) & -\overline{G}(k) \\ \overline{G}^T(k) & 0 \end{bmatrix}\begin{bmatrix} K^{*T}{}_s(k) \\ \Lambda^T(k)\end{bmatrix} = \begin{bmatrix} H(k)\overline{P}_s\left(k/k-1\right) \\ \overline{Z}^T(k)\end{bmatrix}. \tag{41}$$

If the matrix $\overline{G}^T(k)W^{-1}(k)\overline{G}(k)$ is not singular, the matrix Eq. (41) has a single solution, and the transfer matrix $K_s(k)$ is given by

$$K_s^*(k) = \overline{P}_s\left({}^k/_{k-1}\right)H^T(k)W^{-1}(k)\left[I - \overline{G}(k)\overline{G}^*(k)\right] + \overline{Z}(k)\overline{G}^*(k). \tag{42}$$

5 Illustrative Example

As a test example, consider the process of an aircraft landing consisting of several stages. In the first of them, the aircraft is guided to the required airport by means of radio guidance equipment. At the second stage, starting from the moment of entering the coverage area of the glide path radio beacon, the pilot directs the aircraft along the selected glide path line at an angle of approximately – 3^0 to the runway. At a height of about 30 m, the final phase begins - alignment. Here, due to the close proximity of the earth, radio beam guidance becomes ineffective. Further planning at an angle of – 30 to the horizon plane also doesn't meet the conditions of flight comfort and safety. Therefore, at the leveling stage, the pilot controls the aircraft in manual mode, focusing on the on-board facilities indications, such as altimeters, and his visual observations. However, in any case, effective aircraft flight control involves the use of an a priori given nominal mathematical model of the aircraft as a control object. In addition, the nominal mathematical model of the control object is a basic element in the construction of dynamic system models that will be affected by disturbances or faults. If we assume that the roll angle at the leveling stage is equal to zero, then the movement of the aircraft is divided into two components: longitudinal and lateral. Further, we confine ourselves to considering only the longitudinal component of the aircraft motion. The small value of the landing trajectory inclination gives grounds to believe that the longitudinal movement of the aircraft during the leveling stage is completely determined by the angles of deflection of the elevators, provided that the pilot maintains the throttle stick in such a position that the airspeed of the aircraft re-mains constant. The small value of the landing trajectory inclination gives reason to believe that the longitudinal movement of the aircraft during the leveling phase is completely determined by the deflection elevator angles, provided that the pilot maintains the thrust handle in such a position that the airspeed of the aircraft remains constant. From the point of view of flight stability and controllability along a given trajectory, the most significant role is played by the short-period component of the longitudinal motion, the linearized equation of which in terms of variable states has the form [29]:

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{1}{T_0} & \dfrac{V_0}{T_0} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \left(\dfrac{1}{V_0 T_0{}^2} - \dfrac{2\xi_\vartheta \omega_\vartheta}{V_0 T_0} - \dfrac{\omega^2{}_\vartheta}{V_0}\right) & \left(\dfrac{1}{T_\vartheta{}^2} - \dfrac{2\xi_\vartheta \omega_\vartheta}{T_\vartheta} - \omega_\vartheta{}^2\right) & \left(T_0{}^{-1} - 2\xi_\vartheta \omega_\vartheta\right) \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ K\omega_\vartheta{}^2 T_0 \end{bmatrix} \delta_\epsilon . \quad (43)$$

where ξ_ϑ – is the damping coefficient in the pitch channel; ω_ϑ – frequency of free oscillation; V_0 – landing approach speed; K – is the amplification factor of short-period oscillations; T_0 – trajectory time constant; δ_ϵ– angle of deflection of the elevator. The parameters of Eq. (43) are determined by the aircraft design features and depend on the coefficients of aerodynamic forces and moments, which are very complex non-linear functions of many parameters and change with time depending on the flight conditions.

However, the processing of the results of flight and bench tests shows that the vast majority of pilots rate the aircraft as a control object as "good" or "satisfactory" if its design parameters are within the following limits: $\xi_\vartheta = 0{,}5–0{,}7$; $\omega_\vartheta = 1–3{,}5$ c^{-1}; $K = 0{,}5–2$; $T_0 = 1–5$ c. In accordance with the instructions of work [26], we will dwell on the following values of the above parameters: ξ_ϑ=0.6; T_0=3,5c; T_ϑ=3,1c ;K_ϑ=1,8 c^{-1};V_0=75мс$^{-1}$, that are consistent with the recommendations of other works, for example [27]. As state variables, we choose the altitude, the rate of its change, the pitch angle and the rate of pitch angle change. This choice has the advantage that all state variables are technically measurable. The discrete equivalent of the nominal model (43) supplemented by the perturbation component has the form [29]:

$$\begin{aligned} &\boldsymbol{s}(k+1) = \boldsymbol{\Sigma}(k+1,k)\boldsymbol{s}(k) + \boldsymbol{\Gamma}(k+1,k)\boldsymbol{u}(k) + \boldsymbol{\Omega}(k+1,k)\boldsymbol{d}(k) + \boldsymbol{w}_s(k); \\ &\boldsymbol{y}(k) = \boldsymbol{H}(k)\boldsymbol{s}(k) + \boldsymbol{v}(k), \end{aligned} \tag{44}$$

where

$$\boldsymbol{\Sigma}(k+1,k) = \begin{bmatrix} 1.000 & 0.0249 & 0.0075 & 0.0001 \\ 0 & 0.9920 & 0.6010 & 0.0072 \\ 0 & 0.0001 & 0.9930 & 0.0235 \\ 0 & 0.0073 & -0.5457 & 0.8829 \end{bmatrix}; \boldsymbol{\Gamma}(k+1,k) = \begin{bmatrix} 0 \\ -0.0043 \\ -0.0209 \\ -1.6417 \end{bmatrix};$$

$$\boldsymbol{H}_y(k) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \quad \boldsymbol{\Omega} = \begin{bmatrix} 0 & 0 \\ T_0^{-1} & 0 \\ 0 & 0 \\ -\Sigma_{042} & -(2\omega_\vartheta)\left[(V_0 T_0)^{-1} + T_\vartheta^{-1} + 1\right] \end{bmatrix}.$$

$\boldsymbol{\Omega}$ – the perturbation distribution matrix according to the recommendations [9] was under the assumption that the perturbations source is the change of the aircraft speed $V_0 + \Delta V$ under the wind influence and the instability of the damping coefficient $\xi_0 + \Delta\xi$. The state vector components were also perturbed by white Gaussian noise $\boldsymbol{w}_s(k)$ in order to take into account modeling errors and the influence of the turbulent wind component. Observation errors were simulated by introducing white Gaussian noise $\boldsymbol{v}(k)$ that is uncorrelated with $\boldsymbol{w}_s(k)$. The above noises had a zero mean value, and their intensity was determined by covariance matrices $\boldsymbol{Q}_s(k) \triangleq \mathcal{M}\{ww^T\} = 0.0081 * \boldsymbol{I}_{(4)}$; $\boldsymbol{R}(k) \triangleq \mathcal{M}\{vv^T\} = 0.16 * \boldsymbol{I}_{(4)}$. The initial conditions were taken as follows: $\boldsymbol{s}^T(0) = \left[\, 0.0\ -3.6\ 0.1\ 0.004 \,\right]^T$; $\boldsymbol{P}(0/0) = 0.01 * \boldsymbol{I}_{(4)}$; $\boldsymbol{s}^T(0/0) = \left[\, 0.0\ 1.9\ -0.1\ 0.004 \,\right]^T$. Since the component $\boldsymbol{\Gamma}(k+1,k)\boldsymbol{u}(k)$ is a deterministic value, it doesn't affect the essence of the evaluation process. In order to simplify the modeling process, we set it to zero, that is, we temporarily assume that $\boldsymbol{u}(k) = 0$, and in the final results we take into account the influence of the actual steering sequence, based on the requirements for the landing trajectory of the aircraft at the leveling stage. The simulation results for the standard Kalman filter are shown in (Fig. 1 a,b).

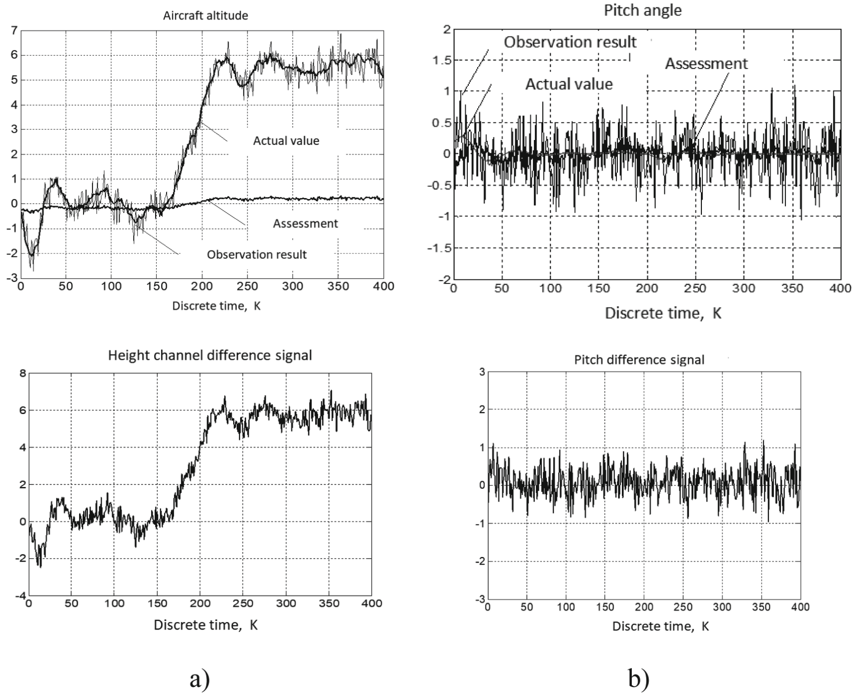

Fig. 1. Results of modeling separate properties of the standard Kalman filter: a) – height channel; b) – pitch angle channel.

Visually, it is easy to see that the difference signal in the height channel is not separated from the influence of disturbances, that is, its average value is far from zero. The consequence is the filtering process divergence starting from the disturbance moment (k = 150) and the impossibility of resolving the fault signal against the related disturbances and noise background. To take into account the effect of the control sequence, we will use the list of main requirements and restrictions specific to the landing maneuver at the leveling stage [27]:

1. The curve for the desired change in aircraft altitude during the leveling process has an exponential and linear component, as shown in (Fig. 2). Thanks to this trajectory, it is possible to ensure the safety and convenience of the landing process. We assume that the leveling stage starts from a height of 30 m and lasts 30 s for an air-craft approaching for landing at a speed of 75 m/s. For the convenience of using the graph, the origin of the coordinates is referred to the runway contact point, and the horizontal axis is graduated in units of distance.
2. At the moment of first touching the runway, the vertical component of the descent velocity should not exceed −0.5 m/s, and the pitch angle should be within 0–10 °. During landing, the aircraft attack angle must not exceed the regulated value of −180. Further, we assume that the synthesized control $\boldsymbol{u}(k)$ satisfies the above conditions.

Under the assumptions made, the change in height during leveling under the action of disturbances $\boldsymbol{d}(k)$ and using the standard Kalman filter has the form shown in (Fig. 3).

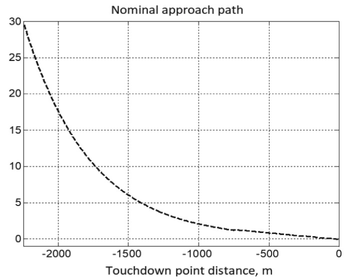

Fig. 2. View of the nominal approach path.

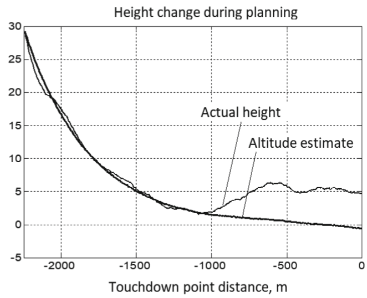

Fig. 3. Aircraft height estimation in the presence of disturbances using standard Kalman filter.

It is easy to see that in this case the actual height is not tracked, and the filtering process diverges. According to previous estimates, the runway contact point shifts to the right by approximately 250–300 m, that can create an emergency situation associated with the aircraft leaving the runway. This is especially critical for airports where, for one reason or another, the runway has a limited length. On (Fig. 4) presents the simulation results for the uncertain inputs filter, synthesized according to the method described in Table 1. The above results show that the height estimate moves towards its actual value only in the asymptotic sense. This will mean that the difference signal of the height channel will not be completely separated from uncontrolled perturbations, that is, only partial decomposition takes place in the time interval $150 < k < 300$. In the future, for $k > 300$, the situation improves. As the estimation process converges, the errors approach zero in the RMS sense, and the difference signal oscillates around the zero value. Also, a similar situation, but in a less pronounced form, takes place in the pitch channel.

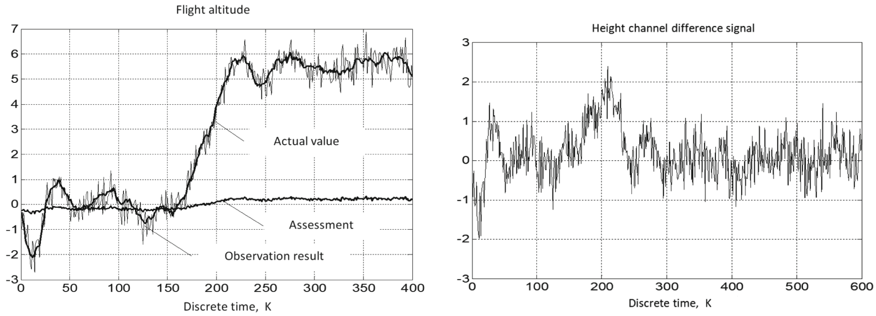

Fig. 4. Height channel estimation results.

The change in the height of the aircraft in the vertical plane, subject to the action of disturbances $\boldsymbol{d}(k)$ and the use of a separate estimation filter, has the form shown in (Fig. 5). It should be noted that the proposed filter, on the whole, adequately reflects the actual change in height, with the exception of the transient process in the area of 1000–500 m, where there is a systematic error. As the estimation process converges, the aircraft crew obtains an objective estimate of the actual altitude and can implement reductions in engine thrust in order to maintain a regulated descent trajectory.

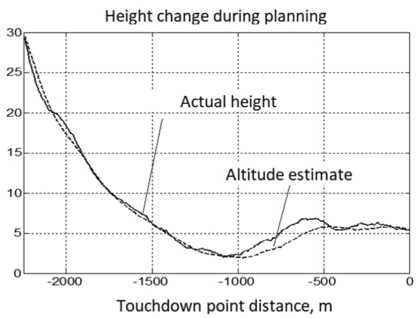

Fig. 5. Height estimation in the presence of disturbances using locally - optimal filter of separate estimation.

6 Conclusion

In the presented work, the solution of the problem of simultaneous separate estimation of faults and the state of a linear dynamic system under the influence of uncontrolled disturbances. An algorithm for recurrent separate filtering is proposed. This algorithm is capable of generating unbiased minimum variance estimates for the case where the fault distribution matrix is a full rank matrix. It is shown that in the case when the rank above the specified matrix remains undefined and is within $0 < rank[\boldsymbol{F}(k)] < p$, optimization remains possible, but in a space of lower dimension, provided that unobserved modes are found in the subspace of persistent modes. Otherwise, the problem of separate estimation has no solution. It is emphasized that the advantages of the proposed separate estimation algorithm become tangibly significant in the absence of a priori data on disturbances or faults, the structure of which remains uncertain. The operability of the method is demonstrated on a meaningful example of an aircraft landing maneuver at the final stage of the landing.

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Conclusions

Keywords

- 5G and Beyond
- 6G
- Blockchain
- CAPEX and OPEX
- CO2 Footprint
- Cybersecurity, IDS and IPS, CIDN
- Digitalization and Digital Transformation
- Digital Economy
- Discrete Algorithm
- Energy Efficiency
- Finite State Machine
- IoT and Smart Office
- ML and AI
- Market Efficiency
- Networked Ergonomics
- Neural Networks
- Process Automation
- QoS and QoE
- Reliability and Control
- Rescue and Emergency Ad Hoc Networks
- Robotics
- SDN and NFV
- Self-Driving Cars
- Signal Processing
- Smart Applications
- Smart Economy
- Smart Home

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- Smart Office
- Smart Shopping
- Starlink
- Terrestrial and Non-Terrestrial Cells
- UAV and Flying Objects
- Unmanned Vehicles
- Wireless Sensor Networks

1 Reference Data about the Book

The book contains 660 pages, 37 chapters each up to 14–24 pages with the preface, introduction and appeared under own edition in close cooperation of the scientists from multiple countries: Germany, Ukraine, Israel, Switzerland, Slovak Republic, Poland, Czech Republic, South Korea, China, Italy, North Macedonia, Azerbaijan, Kazakhstan, France, Latvia, Greece, Romania, USA, Finland, Morocco, Ireland, United Kingdom.

2 Reader Circles and Target Groups

2.1 Target Group 1

The topics to be addressed are definitely of interest to **Postgraduates**: **Graduated Engineers** and **Professionals** who have been active in the telecommunications industry for a while and want to get to know the emerging and innovative computer network architectures, Digital Transformations and Smart Applications, network function virtualization, advanced network technologies, IoT, energy efficiency and security do. The researchers are also involved in the discussion about usable platforms, protocols and best practices.

2.2 Target Group 2

The future book is suitable for **teaching specialist lecturers and professors**. It addresses a holistic view of QoS and QoE, which become nowadays via Digital Transformations less technically and more socially driven. This includes aspects of energy efficiency and ecology (Green IT), security (Secure Transactions, Blockchain-supported IoT) and comfort (QoE based always on). Each chapter contains a real system example. The book has a summary and an outlook as well as further source recommendations.

2.3 Target Group 3

The future book is suitable for **Undergraduates too**: students of universities and technical high schools can access the work as e-book via so-called Springer links.

3 How to Read It?

The material of the presented book covers the latest research results in, but is not limited to, the following research topics. Therefore, we recommend to study the material on the given sequence through the listed topics for better comprehension:

- EMERGING NETWORKS ACCELERATE DIGITALIZATION
  - Emerging Networking: what is it in the future?
  - Digitalization Age, Digital Transformations, Networked Process Automaton
  - Impacts of Smart Economy and Digitalization on Market Efficiency
  - IoT in Emerging Scenarios
  - Robotics and UAV-Unmanned (Aerial) Vehicles, Self-Driving Cars, Discrete Vehicle Automation Algorithms
  - Functional Stability in Emerging Networks
  - Node Reconfiguration and Advanced Routing
  - Reliability and Control in Emerging Networks
  - Networked Sustainability, QoS and QoE
  - Intelligent Connectivity
  - SDN Protocols
  - Traffic Modelling and Simulation
  - Rescue and Emergency Networking
- SMART APPLICATIONS MEET DIGITALIZATION
  - Advanced Software Approaches and Process Models
  - Smart Applications: Smart Information Systems, Smart Office, Smart Home, Smart Shopping, Smart Building Management
  - Highly Decentralised Networking: Adaptation, Coordination, Highly-Distributed Applications
- 5G AND BEYOND
  - 5G and Beyond: Bird Perspective, AI, ML, and Deep Learning, Blockchain
  - Quo Vadis: 6G/NET-2030 goes terrestrial or satellite-based?
  - Polarization and Radio Wave Decay
  - Towards 6G: SpaceX/Starlink Technology, RAT, “Post-Shannon”
  - SAT Radio Networking

- DATA SECURITY FOR EMERGING NETWORKING
  - Data Security for Emerging Networking
  - Cybersecurity: Honeypotting, Intrusion Detection, and Intrusion Prevention Systems and Networks
  - Cryptography and Steganos for Emerging Networking
  - Potentially Dangerous IoT and Networks
  - Blockchain Techniques
- EMBEDDED SYSTEMS AND NETWORKED AUTOMATION
  - Embedded Systems and Networked Automation
  - Networked Control for Embedded and Electronics
  - Modeling, Simulation, Visualisation in Networks
  - Networked Ergonomics: Lighting, HVAC, Smart Home, Smart Office
  - Networked PHY Modelling and Visualisation
  - Neural Network Architectures.

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