Modern Views in the Analysis and Evaluation of Command and Control Systems

Teodora Georgieva
Rakovski National Defence College
Defense Advanced Research Institute
Sofia, Bulgaria
t.georgieva@rndc.bg

Ivo Radulov
Rakovski National Defence College
Defense Advanced Research Institute
Sofia, Bulgaria
i.radulov@rndc.bg

Abstract—**The digitalization of the battlefield creates conditions for an unprecedented enlargement in mobility and parallelism of combat operations. The resulting effect is the increased complexity in implementing the command and coordination functions of the command and control (C2) systems. C2 networks, as the communication infrastructure of C2 systems for issuing orders and disseminating information in real time, are a key element for data exchange between commanders, troops and other related organizations. The characteristics and evolutionary behaviour of C2 networks are described by complex hierarchical associations, interwoven communication links, and dynamic changes. It is their complexity that has become the subject of innovative research approaches and created some of the latest scientific products in the field of C2 systems. The research focus in this report is directed at presenting and comparing typological varieties of modern networked C2 approaches – hypernetworks and supernetworks. Hypernetworks are neural networks that generate weights for another neural target network, and are useful in describing C2 networks with complex levels, intertwining connections and dynamic topology. Supernetworks are a networking technique that consolidates multiple smaller networks into a larger one, simplifying routes and reducing their size. The comparison of the particular variations of the theories is carried out in order to identify the areas of application and solved tasks. References to the C2 networks of the C2 systems in the Bulgarian Armed Forces are provided.**

Keywords—Command and control systems, command and control networks, hypernetworks, supernetworks.

I. Introduction

C2 networks, as the communication infrastructure of C2 systems for issuing orders and disseminating information in real time, are a key element for data exchange between commanders, troops and other related organizations. The characteristics and evolutionary behaviour of C2 networks are described by complex hierarchical associations, interwoven communication links, and dynamic changes.

A. Traditional Network Model

Network models based on graph theory are a powerful tool for solving a lot of practical problems related to optimization and analysis of systems (including C2 systems), where interactions between elements can be represented graphically. Their structure is operationalized by nodes (objects or states in the network) and edges, which represent the connections between vertices. Edges can have weights that denote costs, distances or travel times between connected vertices and allow optimization of the network according to various criteria. Nodes, edges, weights are analysed and visualized by various mathematical algorithms and formulas. Traditional networks usually follow a hierarchical structure, where devices and resources are organized into clearly defined layers and roles. They use standard network protocols, and their management often requires centralized administration and configuration [1, 2].

Despite the wide application of classical network models in command and control (C2) systems, their functioning in this area is accompanied by a number of limitations and shortcomings. Modelling and management of the system are difficult or impossible as the complexity of the network increases or in the presence of dynamic processes. Classical models are unable to reflect the dynamic aspects of real-time interactions, which is essential for effective command and control. Most developments cannot cope with unstructured (incomplete or inaccurate) data, they are unable to integrate different types of data into a single graph model, and do not offer sufficient tools for analysing complex scenarios and relationships. Classical graph models can be too static and inert, as they do not offer enough flexibility to quickly adapt to changing conditions or requirements. The inability to integrate with new technologies, platforms, and services

that contain the potential for improving management and command is another of their limitations [3, 4].

The outlined shortcomings show the areas that modern approaches are overcoming to achieve more effective C2 systems.

B. Hypernetworks and Supernetworks

Hypernetworks and supernetworks are alternative and complementary models to traditional graphs in the organization and management of network structures.

Hypernetworks are neural networks that generate weights for another neural target network and are useful in describing C2 networks with complex interweaving connections and dynamic topology. They represent an extension of standard networks in which nodes (or vertices) can be connected not only by single edges, but also by multiple edges, which allows for more complex interactions and structures. Hypernetworks offer multi-level interoperability, allowing integration and information exchange between them, and are often used to integrate data and services from different platforms and other sources [5].

Supernetworks are Internet Protocol (IP) networks that consolidate multiple smaller networks into a larger one, simplifying routing and reducing their size. They are typically more structured and organized than hypernetworks and can include existing networks working together to achieve common goals. They are often used to optimize resources, manage traffic, and improve the efficiency of network operations [6].

The main difference between hypernetworks and supernetworks is their structure and functionality. Hypernetworks are more flexible and integrate different networks, while supernetworks are more structured and pool network resources for optimization and efficiency.

A comparison of hypernetworks and supernetworks with traditional graph models outlines the following advantages of the former for C2 systems. Hypernetworks and supernetworks offer opportunities for decentralized management, flexibility, and adaptability in response to changing conditions or new requirements, which is essential for the speed of response in a combat environment. They are characterized by increased reliability, security, and protection of communications through duplication of connections and resources or through complex protocols and security mechanisms that increase the invulnerability of the network in the context of military and strategic operations. Hypernetworks and supernetworks have significant advantages in terms of data processing capabilities – they allow for parallel processing of multiple data, processing of complex data and information in real time, and working with large volumes of data and information, which is essential for the speed and quality of operational and strategic decision-making. They can integrate different technologies and platforms, which allows for flexible communication and coordination between different units of the system. Through effective resource management, hypernetworks and supernetworks can minimize losses and maximize the performance of C2

systems. Overall, they offer greater adaptability and connectivity between different networks and systems, while traditional networks are characterized by a stricter hierarchy and centralized management. Hypernetworks and supernetworks are extremely useful for C2 systems when they have to function in complex and dynamic environments or to improve security and coordination in complex situations.

II. MATERIALS AND METHODS

The method used is a comparative analysis of some of the latest scientific research in the field of hypernetworks and supernetworks development in the C2 systems. The main emphasis is on identifying the conceptual aspects of the models, although the technical parameters tested in the simulations are also noted, which generate conclusions about the effectiveness of the proposed solutions. The mathematical formulas with which the models are described are not presented in this report. The aim is to reach a wider audience through theoretical extraction. The cited studies were carried out by a team from the Chinese scientific academy in the field. At the same time, the models under consideration, in addition to being unique in their adopted research approach, also have a mutually complementary theoretical value. All authors in their conceptualizations proceed from the OODA (observe, orient, decide, act) ring theory of a C2 network, according to which combat process mainly includes three basic activities: battlefield situational awareness, decision command formulation, and firepower strike implementation. References to the C2 networks of the C2 systems in the Bulgarian Armed Forces are provided.

III. RESULTS AND DISCUSSION

A. Models of C2 Hypernetworks and C2 Supernetworks

The unprecedented increase in battlefield mobility, the expansion of the theater of operations, and the complexity of command and coordination relationships place higher demands on the functional characteristics of C2 networks [7]. The requirements for the inclusion of heterogeneous nodes, multiple connections, and time-varying topology complicate the traditional network model and form an avenue for the introduction of new advanced alternatives.

This report will analyse and compare several models of C2 hypernetworks and supernetworks, whose a priori assumptions are built on an identical pattern of structural simplification of the combat process based on the main functions and responsibilities that combat units perform - battlefield situational awareness, formulation of a command for a decision to act, and the execution of a firepower strike "Fig. 1".

The three processes are represented in C2 hypernetworks and C2 supernetworks through three types of nodes - sensor, command, and combat. Each of these units forms its own unique subnetworks, which intertwine with each other to form a topological structure with multiple overlapping horizontal and vertical layers. The core of the network is the command subnet, which forms two interlayer networks with the sensor and firepower

nodes. The result is a three-layer, five-network cross-over structure "Fig. 2".
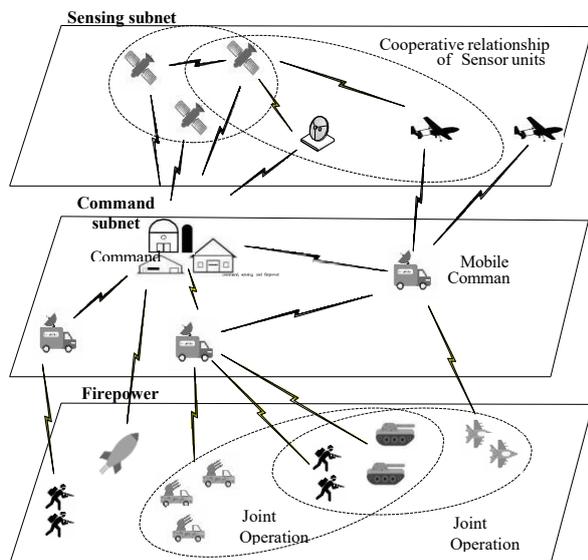
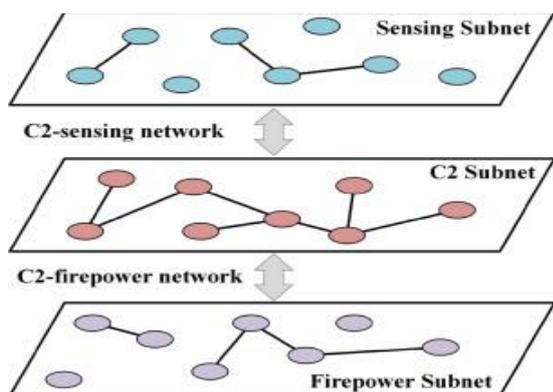

Fig.1 Example of a modern C2 network [10].

Fig.2 Abstract visualization of a C2 network [9].

The paper will present three models for C2 hypernetworks and C2 supernetworks, which, based on the simplified pattern of the combat process and applying unique algorithms, offer further conceptualizations of certain aspects of the behaviour and management of evolutionary C2 hypernetworks or C2 supernetworks. Wang et al. (2019) [8] propose an algorithm for hierarchical transformation of the layers of an evolutionary C2 hypernetwork model. Chen et al. (2023) [9] define rules for the evolution of different types of nodes and edges and propose steps for the dynamic development of a C2 hypernetwork. Chen et al. (2019) [10] propose a model for a C2 supernetwork based on the priority of the synergy of attributes, and analyse the rules for the evolution of the network hyperedge. The evolutionary aspect of the models means that networks are not static, but develop and change over time, which may include adding or removing nodes, changing the connections between them, and adapting to new conditions or external influences. At the same time, in

order to reflect real-world performance, the authors adopt a number of constraints on the evolutionary behaviour of the structure and capabilities of C2 hypernetworks and C2 supernetworks. The first constraint is on the type of connected edge. It is assumed that the transmission of information between a sensor node and a firepower node must go through a command node, and thus the direct connection between a sensor node and a firepower node is not considered in the evolutionary process. The second constraint is on the uniqueness of a command link. In order to guarantee the uniqueness of a given command, sensor and fire strike nodes can only be directly connected to one C2 node. The third constraint is to combat the link integrity constraint. Only a complete combat link can be formed for combat effectiveness, which means that in the event of an attack, operations such as the removal and restructuring of isolated nodes must be carried out.

The following sections will present the main parameters of the models. The comparison of individual variations is carried out in order to identify the areas of application and the tasks being solved.

a) Hierarchical Evolutionary Model of C2 Hypernetwork

Based on the presented three-layer pattern, Wang et al. (2019) [8] build a model that uses the characteristics of nodes and their interactions as basic concepts. Each node has an identification number, uniqueness, attributes (the set of node functions, which is a vector), performance (the ability of the node to process data, perform calculations and communicate with other nodes). The information interaction between the types of nodes in the hypernetwork forms sets of hyperedges, described by a mathematical equation. An edge of the graph that contains several (arbitrary number) nodes is defined as a hypergraph. The interaction between different types of nodes is shown in "Fig. 3".

The figure illustrates the three layers of nodes, which can be grouped both within a given layer and in a hyperedge with nodes from another layer. In the general case, command nodes receive information from multiple sensor nodes and are connected to them via a hyperedge. Information exchange is possible between multiple command nodes, which is visualized by hyperedges between them.
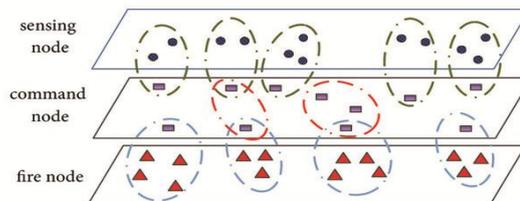

Fig.3 Wang et al.'s (2019) hypernet model for command and control [8].

One command node is authorized to command multiple fire nodes to carry out a fire attack against combat targets. A command node and multiple fire nodes are connected via

a hyperedge to indicate the downward connection to the fire attack command. Thus, the C2 hypernetwork model based on a hypergraph is able to relatively adequately describe and represent the interaction and influence between nodes.

The C2 hypernetwork model is represented by mathematical equations [8]. The applied conceptual approach includes a hierarchical modelling method that combines the hierarchical characteristics of the C2 network and the characteristics of the multilayer structure of the hypernetwork through the formula $K(M_n + 1)$, where K is the total number of layers of the C2 network to be built, and M_n is the number of new nodes added in layer n. The model also analyses the frequency of node joining in each layer. The principle of operation of the hierarchical evolutionary model includes three steps: initialization (the hyperedge connects the nodes), increasing the number of network nodes (new nodes are connected to new nodes in a hyperedge according to probability) and hierarchical transformation (when the number of nodes increases in a given layer, a new layer begins to be built). The hierarchical process of evolution of the C2 hypernetwork deployed according to the defined steps is visualized in "Fig. 4".
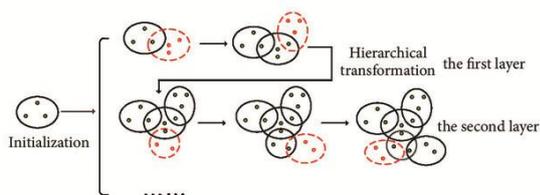

Fig.4 Diagram of the hierarchical evolutionary process of the C2 hypernetwork [8].

Theoretical analysis of evolutionary algorithms provides evidence that the degree of nodes in the C2 hypernetwork follows a hyperdegree distribution and has scale-free characteristics.

The model is verified by simulation, which shows that the characteristics of the C2 network "the rich are richer" are satisfied, i.e., a node in the network that already possesses many links or resources is more likely to attract even more links or resources.

In order to analyse the characteristics of the hierarchical evolutionary model of a C2 network, the changes of measurement indices such as average degree, clustering coefficient and modularity degree are simulated and analysed. The results show that the values of all three coefficients are significantly higher than those of other networks.

The simulation examines the invulnerability of the C2 hypernetwork to targeted or random attacks. The metric used is the natural connectivity coefficient. The results show that when the hypernetwork encounters targeted or random attacks, the natural connectivity of the hierarchical hypernetwork is higher than that of other networks with an increasing number of attacks, and the numerical value changes slowly. This means that the invulnerability of the hierarchical hypernetwork model is better than that of other network models.

In conclusion, although it is built on the hypothesis of simplifying information warfare, the hierarchical evolutionary model offers a framework that improves the efficiency of the C2 network, operates with heterogeneous nodes, multiple connections and different layers, offers better connectivity between nodes and greater reliability of the organizational structure. The model has an important reference value for building a C2 network topology [8].

b) Dynamic Evolutionary Model of C2 Hypernetwork

The evolution of the C2 hypernetwork refers to the process of dynamically adjusting the network structure in accordance with the combat process and the switching of combat missions to achieve coordination and cooperation between subnetworks. Chen et al. (2023) [9] proposed a method for dynamic evolution of the C2 hypernetwork, in which the dynamics of behaviour are categorized as the addition and deletion of combat units (nodes) and the establishment and dissolution of combat relationships (edges). The characteristics of the dynamic evolution of the C2 hypernetwork are the heterogeneity of nodes and edges; dynamic changes of nodes and edges; synergy between homogeneous nodes. The interactive relationship between nodes of the C2 network is expressed in a network model with dynamic characteristics of edge connection.

Behaviour addition. One way to improve the combat capabilities and efficiency of network transmission is to add new combat units (nodes) and establish new connections (edges) in response to updated operational requirements. Three categories of node additions have been described, which are described by mathematical formulas (see Chen et al., 2023). The main theoretical considerations for each process are as follows:

- Adding a C2 node. The probability of joining a C2 node decreases as the command hierarchy increases. If the added C2 node joins the highest command hierarchy, a cooperation boundary is established with all C2 nodes in the hierarchy.
- Adding firepower nodes. The purpose of adding a firepower node is to improve the combat capabilities of the C2 network or to compensate for the lack of current combat capabilities. The attributes of a firepower node typically include mobility, fire suppression, and air defence capabilities.
- Adding sensor nodes. The addition of sensor nodes is done to increase the type or extend the range of intelligence, thereby improving the network's understanding of the battlefield situation, allowing C2 nodes to make more accurate command decisions.

In parallel with the addition of nodes, new joint connected edges can be added. The act helps to improve the ability to share information and carry out joint commands. Three rules are defined for adding edges: for cooperation with a C2 node; for cooperation with firepower nodes; joint edges to a sensor node.

Deletion behaviour. In the C2 hypernetwork development model, node deletion is considered within two main scenarios: normal node elimination and as a result of enemy fire.

- Normal node elimination. Deletion of poorly connected or non-working nodes.
- Elimination of nodes during enemy attacks (random or intentional attacks).
- Active deletion of connected edges. The hyperdegree values of the nodes at both ends of the connected edge are used to measure the importance of the edge. Nodes with low attributes or those that have acquired them during resource consolidation are likely to be actively deleted.

Behavioural Restructuring. In the process of C2 network evolution, isolated newly created nodes may be added to the positions of deleted nodes. In these cases, these isolated nodes need to be reorganized to improve the invulnerability of the C2 network. Common reorganization methods include level-up, cross-level, transfer, and upgrade. Due to the strict hierarchy of the C2 network and the synergy between nodes in the same command hierarchy, the authors only consider the node transfer method.

- Transfer and Reorganization of C2 Node. When a C2 node in a certain command hierarchy is deleted, the subordinate node directly connected to it loses its command relationship, and then needs to be reorganized.

Simulation analyses show that the proposed model has the characteristics of a scale-free network and obeys the law of hyperdegree distribution. Parameter analysis shows that in the network construction stage, the evolutionary behaviour is mainly manifested by the increase of nodes and edges. At the same time, node deletions also occur due to normal elimination. The results show that the increase in the number of new nodes increases the size of the network, and the characteristics of network scarcity also gradually appear. At the same time, the average length of the information transmission path between nodes increases and the average clustering coefficient of the network decreases. In addition, the increase in edges optimizes the organization of the internal connections of the network, improves the information interaction ability and the proximity between nodes, thereby shortening the average length of the network path and increasing the average clustering coefficient of the network. Due to the fact that the number of steps in the network development increases, the average path length of the network shows a decreasing trend.

The analysis of the network invulnerability is carried out in the confrontation stage, when the C2 network is subject to external attacks. In this situation, the behaviour of the network evolution is mainly dictated by the probability of removing nodes and edges. For two typical attacks, random and intentional attacks, the removal methods can be classified as random and preferential with hyperdegree. Under random attacks, the network performance decreases slowly. The reason is that random attacks have the same probability of removal for each node, and the C2 network has an approximate tree structure and an interlayer cooperative structure, which allows compensation mostly by cooperative edges. Intentional attacks are aimed at critical nodes and the clustering coefficient and the combat effectiveness decrease significantly more than random attacks. The simulation shows that the relatively highest invulnerability shows a network in which the hyperdegree is only one of the considered factors and takes into account the reorganization behaviour of isolated nodes [9].

In summary, the results of the simulation analysis show that the dynamic evolutionary model of the C2 hypernetwork is able to maintain relatively good network performance under both random and intentional attacks.

c) Multilevel C2 Supernetwork Model Based on Attribute Synergy Prioritization

Chen et al. (2019) [10] propose a multilevel C2 supernetwork (MC2S) model based on attribute synergy prioritization. The approach adopted takes into account the differences between inter-layer and intra-layer hyperedge generation, as well as the differences between nodes of the same class that have different attributes.

In addition, strategies for generating intra-layer hyperedges in the MC2S model based on attribute synergy prioritization, as well as methods based on a local world (LW) model for generating inter-layer hyperedges of the network, are described.

The MC2S model is based on the described three-layer pattern consisting of command, sensor, and fire subnetworks. Within the model, the cross-layer structure of three layers and five networks is considered as a supernetwork or "network of networks".

In the sensor layer, the node attributes are defined as communication information collection capability, image information collection capability, and intelligence data collection capability.

Firepower nodes have four operational capability attributes, namely, advance capability, firepower neutralization capability, air defence capability, and equipment maintenance capability.

The core of the network is the command subnet, which forms (two) interlayer networks with the sensor and firepower level nodes. The command scope and command level of the network are with command levels that are consistent with the organizational structure of the Army C2 systems.

Attribute synergy prioritization is applied as a comprehensive boundary generation strategy to determine the attraction between nodes and the connection between them. The rules for intra- and inter-layer hyperedge generation are based on attribute complementarity. In intra-layer networks, cooperative intra-layer hyperedges are formed between firepower and sensor nodes based on their attraction to each other (as determined by the attribute

synergy rules) to provide a wide range of operational capabilities required by a combat mission. In inter-layer networks, inter-layer C2 links with LW selection characteristics are formed between command nodes and firepower/sensor nodes based on their hyperedges. This process ensures the efficiency of information transfer between nodes of the intra-layer cooperative hyperedges. In summary, attribute synergy prioritization forms the basis of the proposed model.

Simulation results show that possessing small-world properties provides high levels of information transmission efficiency between combat units of a C2 network. The MC2S model has a short average path length as well as a large clustering coefficient. In general, low average path lengths allow combat intelligence to quickly reach a target node, while large clustering coefficients indicate that nodes are closely connected to each other, which increases the efficiency of command issuance and joint combat.

The hyperdegree distribution of the model approximately adheres to a power-law distribution and therefore exhibits scale-free properties. Most of the sensor and fire nodes possess very low hyperdegrees, indicating that these nodes will perform their missions independently in most circumstances. However, the distribution is distorted at high hyperdegrees and in these cases deviates from the power law.

Nodes with significantly high hyperdegrees (such as reconnaissance satellites) can participate in different missions through cooperative relationships. The class-specific hyperdegree distribution of command nodes is that there are high connection probabilities at low hyperdegree and low probabilities at high hyperdegree, which indicates that the C2 network possesses the characteristics of centralized command. In addition, the hyperdegree distribution of command nodes shows a significant "lift", and most of the command nodes around the peak of the lift are third-level nodes, which indicates that the base-level command nodes need to be connected to a large number of sensor and fire nodes to direct battles and obtain real-time information for battle. Thus, this structure helps to divide the workload of high-level command nodes and improve the efficiency of combat command.

The next parameter to be analysed is the efficiency of the network superlinks. It is assumed that the mission link in a supernetwork is defined as the shortest chain of hyperedges between layers between sensor nodes and firepower nodes. Generally, the focus of network evaluations in the real world is the overall combat capability of the network.

This metric can be expressed using the total number of missions superlinks in a network and the average efficiency of these mission superlinks.

The dependence of the overall network combat capability on the tuning parameter of the joint propensity of the surveillance and firepower subnetworks indicates that increasing the number of interacting edges will effectively increase the network combat capability.

The author team considers the cost of network construction as an important factor to be considered when developing C2 networks. The test results show that it is cheaper to increase the network combat capability by improving the level of cooperation in sensor nodes than by improving the level of cooperation in firepower nodes. Therefore, it is important to increase the level of interconnection in the sensor subnetwork during the construction of C2 networks in the real world. Since the construction of C2 networks is a multi-attribute decision-making problem that is constrained by various factors, the authors emphasize the need to holistically consider mission difficulty, network cost, and network performance during the configuration of C2 network parameters.

In any mission that requires a specific set of node classes, the combined cooperative combat length of this set is the sum of the shortest path lengths between any two nodes divided by the maximum number of links between the nodes of this set. Since C2 networks are intended for use in combat missions, the efficiency of communication between nodes participating in a mission is an important indicator for determining the cooperative engagement capability of a C2 network. The authors propose the combined cooperative combat length as an indicator of this capability in supernetwork models that contain nodes with different classes and attributes.

The information transmission efficiency of the considered model is proven to be significantly higher than that of other models and is most pronounced in simple missions. Thus, the characteristics of the MC2S model are suitable for forming effective and stable cooperative structures in nodes with different attributes during the execution of certain combat missions. In this way, the combat capability of the network is proven to be greater than that of individual nodes [10].

Network invulnerability indicates the ability of a C2 network to maintain connectivity when attacked. In all C2 network models, the network performance decreases slowly in the presence of random attacks; however, it degrades rapidly when subjected to selective attacks. Thus, these C2 network models are robust against random attacks but weak against selective attacks. Since these network models have significant preferential attachment properties, there are a small number of nodes that play a central role in these networks, and the removal of these nodes through selective attacks can have a significant impact on the C2 network. Nevertheless, the MC2S model maintains the highest overall level of combat capability in both scenarios and shows an excellent degree of invulnerability.

Appropriately adding connections between nodes in the firepower layer or sensor nodes in a C2 network will help prevent key nodes from being isolated when the network has suffered a failure, ensuring that the network's mission connections remain intact during combat, thereby improving the network's ability to sustain combat.

In conclusion, the simulation experiment results prove that the proposed MC2S model possesses small-world properties, scale-free properties of supernetworks, and high level of network robustness. In addition, the hyperedge

connection based on attribute synergy prioritization in the model significantly improves the cooperative engagement capability of the network. In summary, the model is a reference for describing heterogeneous edge connections in C2 networks, analysing network performance, and deploying complex networks for combat missions in the context of the integrated joint operations doctrine [10].

D. Application of Hypernetworks and Supernetworks in the Context of C2 Networks of the Bulgarian Armed Forces

The communication and information characteristics of the military CIS networks are a matter of secret nature and, according to some experts, the general system does not include hypernetworks and supernetworks. The defining concept is Integrated CIS [11], [12], [13], [14]. Regardless of the fact, supernetworks can be indirectly established as applicable components in the system architecture. Supernetworks, also known as Classless Inter-Domain Routing (CIDR) and the process of combining multiple networks into a larger network, allows for more efficient use of the IP address space, leads to improved scalability and reduced network load. "Classless routing" between domains (Classless InterDomein Routing - CIDR) is widely implemented in the Bulgarian Integrated CIS [15].

An example of the presence of a supernetwork includes the infrastructure of one of the latest purchased digital communication and information means for the Land Forces of the Bulgarian Army for equipping a brigade and battalion command post [16]. The new equipment allows for the transmission of voice, data and video in real time from a camera mounted on the helmet of the foot soldier to the battalion commander and to higher levels, depending on the mission. The acquired information system for command and control provides services at three levels: foot soldier - combat vehicle - command post. The system supports the operational staff in joint planning and execution of missions, building a generalized picture of the ground situation and enabling commanders at different levels of command to make the right decisions and promptly give their orders to the last soldier "Fig. 5".
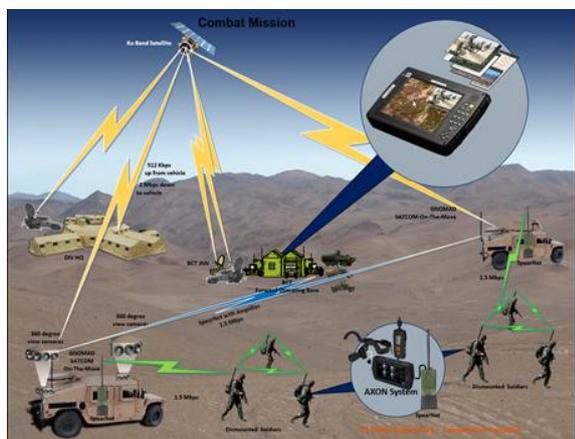

Fig. 5. Supernetwork model "foot soldier – combat vehicle – command post"

In addition, part of the new equipment are radio relay radios, providing stable broadband communications with a transmission speed of up to 428 Mbps, through which the necessary services are provided to the control points. The installation of dual-channel VHF radios, which allow simultaneous voice communication and data transmission at speeds of up to 5 Mbps, has a software-defined architecture and supports rapid updates in the field. Routing and cross-connect capabilities ensure the sharing of critical ISR for voice and data with different networks and subnetworks. The "foot soldier – combat vehicle – command post" model is an alternative version of the "sensor layer – command and control system – fire layer" model, which was considered in the theory review.

A problem with national defence capabilities is that the systems in place "provide services – voice, data and video, but they are built on the basis of different technologies and the compatibility between them is highly limited, and in some cases even impossible" [17, p. 127]. It is recommended to "generate a strategy for building the communication and information system, through a technologically derived concept for rearmament and with capabilities for an adequate response to hybrid threats" [17, p. 130]. In such a context, the application of hypernetworks and supernetworks gains its place.

CONCLUSIONS

Hypernetworks and supernetworks offer compensatory mechanisms to overcome some limitations of traditional graph theory when applied to C2 networks. The comparison of the individual variations of the conceptual approaches was carried out with the aim of identifying the areas of application and tasks to be solved. Each of the described models offers a specific contribution to improving aspects of the functioning of a C2 network in combat conditions. The hierarchical evolutionary model of Wang et al. (2019) presents the algorithm for implementing a hierarchical transformation of a C2 hypernetworks. Chen et al. (2023) illustrates the rules for dynamically changing the behaviour of an evolutionary C2 hypernetworks by describing the steps of removing, adding and reorganizing nodes and edges in the network. Chen et al. (2017) deploys a multi-level model of a C2 supernetworks by prioritizing the synergy of attributes. The three models are based on an identical three-layer pattern of the combat process and represent scale-free networks that obey a hyper-level distribution. All three models demonstrate good performance in terms of network invulnerability. Specific practical implications for C2 systems are the following:

- The performance of the C2 network is higher when optimizing the cooperation of sensor nodes than by adding fire nodes.
- The resilience of the C2 network is much higher under random attacks than under directed attacks. The destruction of key nodes can be compensated by adding additional connections between nodes in the firepower layer or sensor nodes.

- Increasing the number of growing edges will effectively increase the combat capability of the whole network.
- The cost is lower if the combat capability of the network is increased by improving the level of cooperation in sensor nodes rather than by improving the level of cooperation in firepower nodes.

In the Armed Forces of Bulgaria, the concepts of hypernetworks and supernetworks are not yet popular enough in everyday use, although in the case of supernetworks, they are recognized as woven into the name of older, classically established terms. The progressive process of modernization of the Bulgarian Army and Armed Forces and the introduction of new technologies in the form of newly purchased equipment puts both types of networks in the focus of attention. This report represents a step in getting acquainted with the conceptualization of the concepts and their widespread use for educational and scientific purposes.

REFERENCES

[1] T. J. Richard, Introduction to graph theory. New York : Dover Pub, 1993, pp. 8-18.

[2] E. Enev, "Understanding the operational environment and determining the center of gravity through network analysis and social network analysis," Bulgarian Science, vol. 05, pp. 8-16, 2020.

[3] M. Révay and M. Líška, "OODA loop in command & control systems," Communication and Information. Technologies, Vysoke Tatry, Slovakia, pp. 1-4, Oct. 2017.

[4] X. Song, S. Y. Zhang and X. C. Shi, "Measurement of network complexity and capability in command and control system," Journal of Statistical Computation and Simulation, vol. 84, no 6, pp. 1232-1248, Jun. 2014.

[5] V. K. Chauhan, J. Zhou, P. Lu, S. Molaei, and D. A. Clifton, "A Brief Review of Hypernetworks in Deep Learning." Artificial Intelligence Review, vol. 57, no 9, pp. 250-279, Aug. 2024. https://doi.org/10.1007/s10462-024-10862-8.

[6] A. Nagurney and T. Wakolbinger, "Supernetworks: An Introduction to the Concept and its Applications with a Specific Focus on Knowledge Supernetworks," The International Journal of Knowledge Culture and Change Management Annual Review vol. 4, no. 1, pp. 1-16, Jan. 2005. https://doi:10.18848/1447-9524/CGP/v04/50227.

[7] C. Pan, X. Chen, Y. Wang and B. Chen, "A method of key links identification in command and control network based on bridging coefficient," in IEEE ICNSC, Zhuhai, China, pp. 1-5, Mar. 2018.

[8] Y. Wang, B. Chen, X. Chen, and C. Pan, "Hierarchical Evolution Model of Command and Control Network Based on Hypernetwork," Hindawi. Journal of Control Science and Engineering, vol. 2019, no. 1, Jan. 2019. https://doi.org/10.1155/2019/5860461.

[9] B. Chen, H. Tao, X. Jiang, Y. Chen, and X. Gao, "Dynamic hypernetwork-based evolutionary model of command-and-control network," Simulation Modeling Practice and Theory, vol. 126, 102759, pp. 1-13, Jul. 2023. https://doi.org/10.1016/j.simpat.2023.102759.

[10] B. Chen, H. Yu, Y. Wang, X. Gao and Y. Xu. "Multilevel Command and Control Supernetwork Modeling Based on Attribute Synergy Prioritization," IEEE Access PP(99):1-1, Mar. 2019. https://doi:10.1109/ACCESS.2019.2903520. [Accessed January 25, 2025].

[11] K. Dimitrov, Planning and Design of Military Communication and Information Networks and Systems: Military Academy "G. St. Rakovski" Press, 2021.

[12] K. Kalchev, "Structure of a Military Communication and Information System Providing Network Connectivity," CIO Chief Information Officer, no. 7, 2010.

[13] I. Hristozov and M. Lambeva, Approach to Integration of Information Systems: Scientific Conference: Military Technologies and Systems for Ensuring Defense, Institute of Defense, Sofia, Bulgaria pp.176-182, 2012.

[14] I. Hristozov, V. Alexandrova, I. Chakarov, Ch. Kostadinov, K. Krumova and R. Angelov, Tools for Modeling Threats and Cyber Intelligence Processes Used in NATO, and Their Applicability: Collection of Reports from the International Scientific Conference: 20 Years of Bulgaria in NATO and NATO in Bulgaria. April 2–4 2024, Military Academy "G. S. Rakovski", Sofia, p. 235-246, 2024.

[15] Hristozov and Kr. Krumova, Computer Networks and Communications, Sofia: Military Academy "G. S. Rakovski", 2023.

[16] D. Mitev, "Digital transformation will cover all formations of the Armed Forces," Bulgarian Army Newspaper, Interviews, December 2023, [Online]. Available: https://armymedia.bg/2023/12/08 [Accessed January 27, 2025].

[17] I. Chakarov, National Defense Capabilities in Integration of Electronic Communication Networks: 30 Years of the Faculty of National Security and Defense 1994 – 2024 Anniversary Scientific Conference November 4, 2024, Military Academy "G. S. Rakovski", Sofia, pp. 123-132, 2024.