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# On Evolution of C2 Network Topology

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# On Evolution of C2 Network Topology

**Abstract:** C2 is shifting from traditional hierarchical organization structure towards more collaborative and adaptive endeavors, with system of systems being rebuilt on a foundation that incorporates agility, focus, and convergence, namely networked in both the theoretical and the operational front. At present, flexible, secure and efficient C2 network topology is one of the fundamental issues for C2 study. Due to the openness and dynamic nature resulting from multi-threat and diversity of mission, and also influenced by factors like link situation, information flow, command and cooperative relationship which interact with each other, the specification, modeling, resolution and building of C2 network topology stand in our research way. In addition, circumstances and mission requirements are in a state of flux, topology reconstruction seems to be built in and it then becomes another monkey on the back. Under complex networked environment, statistic based topology model is of significance for constructing and maintaining an expected topology. This paper, after summarizing the topology requirements of C2 networks in the eye of agility, security and performance, examines the existing typical topology models and points out the deficiencies against the requirements. Finally, existing problems, open issues are analyzed and research approaches are proposed for reference.

# 1 Introduction

The conclusion of the Cold War, with the associated opposition of red and blue forces, has determined the refocusing of the defense activities and strategies toward the development of means that can comply with rapid-force deployment to cope with a variety of missions spanning from peacekeeping to “cover-up” operations [1]. This transformation process has been dramatically accelerated by the raising of the asymmetric threat that is directed to people, places, and infrastructures. As a result, joining the traditional threat, the asymmetric threat whose battlefield turns pervasive and whose environment is a myriad of ever-changing, interdependent variables causes further complications in command and control (C2) where it is hard to achieve information superiority for decision-making. On the other hand, rapid development of information technology, especially network technology and communication technology， provides a spur for networked C2. C2 networks offer geographical decentralization, concealment, adjacency and rapid reorganization of C2 elements by relying on the abilities of whole network instead of the survival of individual units, which restricts complexity and uncertainty, will increase the probability of correct decision-making, so will surely be the shape of things to come [2-3].

In recent years, United States, Russia and NATO have rushed to make a huge investment in development of networked C2 systems that are getting more and more enormous and complex. The U.S. proposed the network centric operations (NCO) program and global information grid (GIG) program, expecting constructing GIG based NCO architecture comprised of C2 grid, sensor grid and engagement grid. Meanwhile, the U.S. Department of Defense (DoD), stepping up the support of the study of network science, brought forward eight key programs of NCO, whose research areas cover global and local performance evaluation and optimization, modeling, simulation and testing of super large-scale networks; self-synchronization, damage-resistance, self-recover, reconstruction of wireless or wired networks whose structure varies with time; optimization of unmanned platform networks based on the self-adaptive behavior of animal colony networks and so on [4]. And that according to a paper of Air Force Research Laboratory, the U.S. air force has planned long ago to study C2 networks, composing the distributed mission training research networks for collaborative research and training via distributed PC-based systems and second-generation Internet technology, focusing on network performance under complex environments through simulation [5].

C2 network is a military information system grounded on the future GIG communication infrastructure which is made of space network, airborne network and surface networks in a dynamic relationship with each other, through access of all levels or various kinds of C2 systems, fire control systems, information support systems, and related equipment etc., providing secure, efficient, and flexible services for situation awareness, decision assistant, C2 of personnel, equipment, and corresponding act.

With the constantly expanding of the scale of networked C2 system and for the uncertainty of topology requirements of diversity of mission and complex conditions, the difficulties for C2 network to control its own structure and to be adaptive and the like are made evident with each passing day. For another, the appearance of tools like graph theory, statistics, fuzzy mathematics and also the introduction of a series of complex network models lend an acceptable formula to analyzing such complex systems and making them available, reliable, and controllable through topology's optimization. Some researchers from the U.S. Naval Postgraduate School started some related work on C2 network, where Strukel examines C2 network's topology model, linkage mechanism, and application with a force evaluation model and fuzzy set theory, and Lee explores the ability of IEEE 802.11b and IEEE 802.16 wireless components in aerial C2 network [6-7]. Moreover, in the last two years, some famous scholars like West, Hansberger, Bowman carried out an in-depth analysis on cooperation, understanding, and trust within C2 network from a cognitive standpoint [8-11]. In addition, Dekker from the Australia DoD studied the impact of network topology on military combat performance, and by performing experiments within an agent-based simulation system, showing the value of some topology properties for enhancing agility and adaptivity of networked systems [12-15]. Jim Lane discussed the imagination of creating a complete collaborative information environment founded on highly capable and scalable advanced sensor networks; Jardosh surveyed the topology control mechanism for wireless sensor networks, allowing network designers to choose the protocol architecture that best matches the goals of their application; while Tangmunarunkit compared network topology generators, and find that network generators based on the degree distribution more accurately capture the large-scale structure of measured topologies, and produce a form of hierarchy that closely resembles the loosely hierarchical nature of the Internet [16-18]. However, few researches integrate the network topology models and C2 networks, let along the means to control C2 network as a whole in real time is absent. Thus, it is far away from the demands in the respects of adaptivity and self-evolution, like self-healing, self-organizing and reconstructing under the condition that mission, environment, command relation and so forth vary with time. In this paper, the status quo, topology requirements and statistical metrics of C2 network are summarized first. Then typical topology models like regular networks, random networks, small-world networks, scale-free networks are examined. In the end, the deficiencies against the topology requirements, the direction of C2 networks evolution and the future work are pointed out.

The rest of this paper is organized as follows. Section 2 interprets various requirements, topology statistical properties, and metrics for C2 networks; according to the metrics, sections 3 compares the typical network models and indicates the drawbacks; section 4 gives the problems that C2 network evolution faces and the way out; the last section concludes this paper and introduces our future work.

# 2 Metrics for C2 Network Topology

In order to manage variety of military missions, like strategic deterrents, joint operations, antiterrorism, peacekeeping, disaster relief etc., C2 networks should be equipped for the capabilities mentioned below.

For one thing, flexibility, including mobility, reconstruction, and agility, refers to the ability to redeploy, converge, cooperate with each other, and adjust corresponding physical and logical elements or links automatically and fleetly, and to realize the C2 network evolution in reason (efficient, security, robust, and low cost).

For another, decentralization and concealment, mean to avoid the space, information or logic center to confuse the other side, and to reduce the probability of being discovered.

The last but not the least, stability and persistence characteristic mean to reduce the negative effects of changes in information flow, configuration transformation due to invalidation of nodes or links, tactic subnet's access in movement and all that, on security, performance of service of C2 networks, i.e., without drastically diminishing the service provided.

In short, the essence of C2 network construction is to gain the self-adaptive capability by dealing with topology planning and reconstructing reasonably and rapidly while guaranteeing high efficiency, security and robustness. These requirements are discussed in detail and then mapped into topology statistical properties as follows.

## 2.1 Requirements

C2 network is a super large-scale logical network grounded on multi-layer dynamic IP physical network comprising land and space communication sub-system and sea, land, air, and space access sub-system that are interconnected. Thus, C2 network is an open and complex system, whose nodes are physically widely distributed and logically mutually connected, whose topology is self organized with key nodes self regulated and mobile nodes choosing access points by themselves, depending on situations. The key characteristics of C2 network topology are then presented below.

1) Adaptivity. Similar to metabolic networks in biological field, the nodes in C2 networks can join or leave the networks without pre-planning or manual configuration, so C2 topology takes on a view of dynamic evolution. Besides, all these nodes may be mobile in the form of subnet or by itself, visiting one place with preference or task demands. Thus the related topology ought to be reorganized in real time by concrete situation [19].

2) Reliability. C2 network should have the link distribution belonged to the family of skewed distributions like power law, simply very many nodes with a very small degree, a moderate number with a moderate degree and a very few with a very high degree. In this way, the topology abilities in fault tolerance and self healing are enhanced since the key nodes and links can be more adaptive and be reconfigured when any node stops working.

3) Credibility. C2 network is a flexible trust network, where the identity of every node is

authenticated, the integrity of every platform is proved, and all network behaviors are evaluated and can be audited and controlled. And then the topology can isolate and restrain the part where viruses are rampant.

4) High-efficiency. C2 network should be evolved with the shortest mean path length and short cut to some originally remote nodes, and also the bigger clustering coefficient, diffusion rate, and bandwidth efficiency. Further, total system performance and corresponding end-to-end quality of service which relies on level and type of transmission data must be provided, and the availability under attack must be guaranteed [20-21].

## 2.2 Statistic Properties

In 1960s, two Hungary mathematicians Erdös and Rény proposed random network theory. In the past ten years, with the introduction of small world effect and scale free structure, lots of studies on statistic nature, model, evolution mechanism, behavior, function and so on of complex networks have sprung up. Here is the explanation of some topology's statistic properties related [22-23].

**Definition 1** Degree $D_a$, is the number of links connected to node *a*; the node with high-degree is named network center or hub. And degree distribution *F(d)* refers to the probability of a node with degree *d*.

**Definition 2** Shortest path length $L_{ab}$, refers to the least number of links between node *a* and *b*. Mean path length $L$, refers to the mean of the lengths of all shortest paths in the network.

**Definition 3** Clustering coefficient *C* refers to the ratio of the number of actual links between neighbors to the number of possible links between neighbors. And if node *i* has *n* neighbors with $k_i$ links actually, the clustering coefficient of node *i* $C_i$ equals to $2k_i/n(n-1)$, and the clustering coefficient of this network to the mean one of all nodes.

**Definition 4** Diffusion Rate *D(k)*, describes the rate at which commodities proliferate throughout a network, in other words, refers to the average of the number of nodes that certain node can reach by *k* links.

**Definition 5** Betweenness $M_a$, is a measure of a node's importance to dynamic behaviors in a complex network, i.e., the number of shortest paths which pass through the node *a*, reflecting the busy node and potential bottleneck in the network, but not the most connected node (hub).

**Definition 6** Path horizon $S_a$, is a measure of how many nodes, on average, a node *a* must interact with for self-synchronization to occur.

**Definition 7** Neutrality is an additional topology structure in a complex network above the minimum required for connectivity, to evaluate the resilience of topology to various situations. Neutrality Rating *N*, is the quantified metric for neutrality, and equals to $(l-n+1)/n$ for a network with *n* nodes and *l* links.

## 2.3 Topology Metrics

According to the findings of early studies on adaptive network in other domains, here gives the concise topology metrics and related interpretation for analysis of C2 network topology [2].

1) Every node should have two links, i.e., link to node ratio $R$=2. Since no appreciable distinction lies in the performance of a topology with *n* nodes and only 2*n* links and that with more links. Furthermore, too many links (>4*n*) may lead to great overhead of cooperation and decrease in the performance of the topology instead.
2) Topology should have a skew degree distribution $F(d)=d^{-\alpha}$, where $\alpha$ ($>0$) is a constant, and then the hub is capable of smooth reconfiguration. For example, the largest hubs can

appear, recede, and then reappear in a different part of the network by re-wiring only about 5 to 10% of the links.

3) Topology mean path length *L* should be relatively small, with small world effect, i.e., lg*(n)*, and in the course of network transformation, the increase of *L* should also remain under the logarithm of related nodes.

4) The overall clustering coefficient should be between 0.1 and 0.25, meaning that on average about 10-25 percent of 3-node collections should be 3-cycles. The distribution of clustering coefficients among all nodes should be skewed, creating the condition that not all nodes in a cluster interact directly with nodes outside the cluster, i.e., the node near center has a high clustering coefficient, which therefore defines the structure of adaptive hierarchy, meeting the operation needs for cohesion and mutual support.

5) Since it is hard to limit the number of nodes with high betweenness (Definition 5) while maintaining a skew degree distribution and meeting the requirements in clustering coefficient etc., betweenness should also be skew in accordance with link bandwidth and node computing resources. And those high-betweenness nodes must be kept separate from one another [24].

6) To produce good self-synchronizing behavior, the path horizon *S* ought to be approximately the logarithm of the number of nodes in the network, i.e., lg*(n)* [25].

7) Neutrality Rating *N* should be between 0.8-1.2 to increase adaptation and decrease susceptibility.

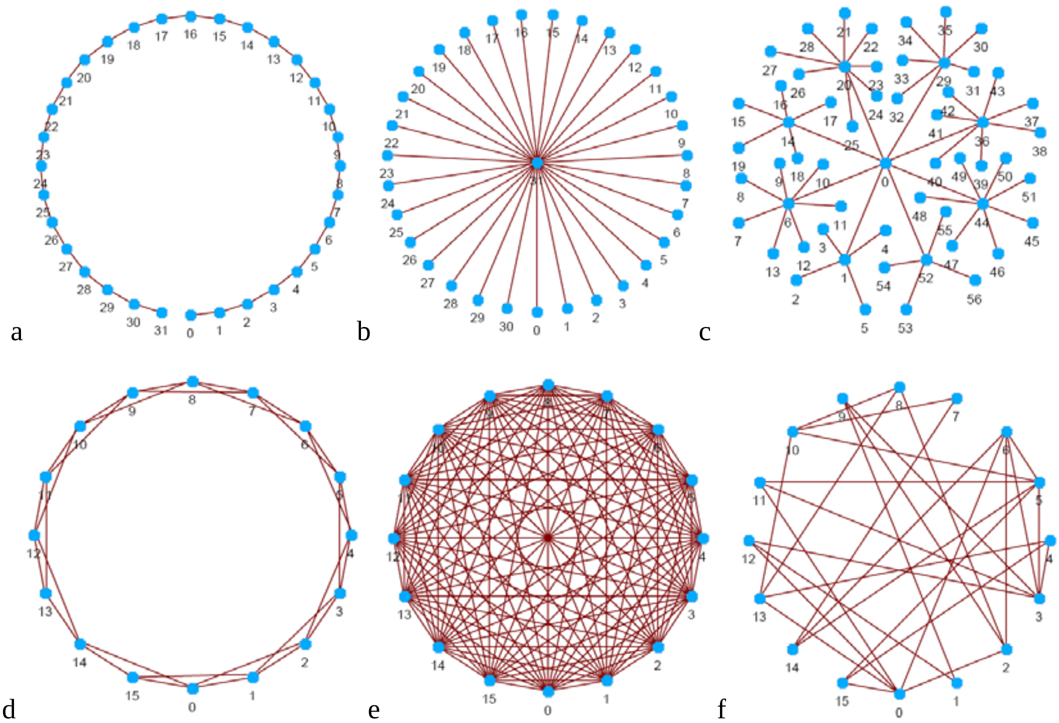


Fig.1 Regular Networks and Random Networks

(a. chain; b. star; c. tree; d. nearest-neighbor (*K*=4); e. globally; f. random )

# 3 Analysis

The system complexity of C2 network mainly focuses on the structure complexity of relationship of links, information, command, and collaboration etc., on the node complexity with intricacy nonlinear acts like bifurcation and chaos, and on the interaction of these complex factors. Topology model gives a qualified and quantified description of network complexity. Are the existing topology models appropriate to C2 networks? Here follows the pilot study on diversified typical networks.

## 3.1 Regular Networks

### 3.1.1 Chain Coupled Networks

A chain coupled network (Fig.1-a) is a line-type topology in which the nodes are all connected with the minimum number of links possible, i.e., one formed by *n* nodes connected one after another with *n – 1* links. When there are a large amount of nodes and the number tends to be limitless, the main topology parameters of chain coupled networks are shown as follows.

1) Link to node ratio $R = (n-1)/n \to 1$

2） Degree distribution $F(d) = \begin{cases} 2/n \to 0, d = 1 \\ (n-2)/n \to 1, d = 2 \\ 0, others \end{cases}$

3） Mean path length $L = (\sum_{i=1}^{n-2}(n-i)(n-i-1))/(n-1)(n-2) \to \infty$

4） Clustering coefficient $C \approx 2/(n-1) \to 0$

Compared to other connected networks with the same number of nodes, the number of links of chain coupled networks is the least, so they are the cheapest and the simplest connected networks. However, chain coupled networks are brittle as there is hardly redundancy for every node. Meanwhile, the mean path length and the delay for information diffusion among the nodes are relatively unbearable. For example, the number of nodes that any node can reach with *n* links is only 2*n*+1. In addition, chain coupled networks define the scale, and the degree distribution is very close to two, because the majority of nodes are connected with only two links. And that the clustering coefficient trends towards zero. All the facts indicate that they are far short of the expectations of C2 network.

### 3.1.2 Star Coupled Networks

A star coupled network（Fig.1-b）is also one of the connected topology with the minimum number of links, i.e., one formed by n-1 nodes connected with the hub only. Star networks’ link to node ratio L is same to that of the chain coupled networks, and other main parameters are given as follows.

1) Degree distribution $F(d)=\begin{cases}(n-1)/n\to 1, d=1\\ 1/n\to 0, d=n-1\\ 0, others\end{cases}$

2） Mean path length $L=2-2/n\to 2$

3） Clustering coefficient $C=(n-1)/n\to 1$

Star coupled network is one of the cheapest and simplest connected networks, whose mean path length is quite short at the cost of single point failure. That's to say a bottleneck exists there, and that all nodes will be alone when the hub does not work. Other flaws are similar to chain topology, so it may be impossible to meet the demands of future C2 network. As a kind of cascading model of star coupled networks, tree coupled networks (Fig.1-c) have the same inherent defects.

### 3.1.3 Nearest-Neighbor Coupled Networks

A nearest-neighbor coupled network (Fig.1-d) is a sparse topology with *n* nodes, where every node is connected to the K/2 (K is an even and less than n) neighbors from the left and the right respectively. For the fixed K, the main topology parameters are listed here.

1) Link to node ratio $R=K/2$

2） Degree distribution $F(d)=\begin{cases}1, d=K\\ 0, others\end{cases}$

3） Mean path length $L\approx n/2K\to\infty$

4） Clustering coefficient $C\approx K/(n-1)\to 0$

The mean path length of nearest-neighbor coupled networks is overlong; moreover it increases linearly with the number of nodes added. Therefore, achieving synchronization in structure may be a nut to crack. And that the scale of this topology is determinate, taking on uniform distribution instead of skewed distribution, And the clustering coefficient drops with accretion of network size, it is then inapplicable to the global C2 network.

### 3.1.4 Globally Coupled Networks

A globally coupled network (Fig.1-e) is the one in which every node is connected to every other node in the network directly with a link, i.e., in a network with *n* nodes, the degree of every node is *n*-1, and the number of links is *n*(*n*-1)/2 in all. The main topology parameters are given below.

1） Link to node ratio $R=(n-1)/2$

2） Degree distribution $F(d)=\begin{cases}1, d=n-1\\ 0, others\end{cases}$

3） Mean path length $L=1$

4）Clustering coefficient $C = 1$

The traits of globally coupled networks include: 1) highest link to node ratio with more links and more subnets than any other type of connected networks and therefore they are the most expensive and complicated connected networks; 2) highest robustness with more redundancy; 3) shortest possible mean path length with commodities proliferated more quickly to the nodes; 4) top clustering coefficient and fixed scale. Since there are too many links for every node, the cost of resisting collisions increases directly with the factorial of the number of nodes, and the number of subnets can easily overwhelm attempts to use them efficiently, and at least it is difficult to calculate the network flux.

For the richest connectivity, globally coupled networks in small group research have proved effective at solving complex problems by laboratory experiments and field studies, but are often slower than more streamlined structures such as hierarchies or spokes of a wheel around a central person, particularly when the groups have no prior experience working together [20]. For military systems, however, the important fact is that fully connected social networks do not scale well. And even if such a system is constructed, the nodes must make an enormous number of decisions about when they will interact, with whom they will interact, and how much attention they will pay to any interaction or offer for an interaction. For running costly and less scalability, it may be simply impractical for C2 networks.

## 3.2 Random Networks

A random network (Fig.1-f) develops when each node has an equal probability of interacting with any other node. Though it seems awfully different from a regular network it can be evolved from a nearest-neighbor coupled network, i.e., one formed in this way: any link of a node selected with probability $p$=1, cut off the link, then rewire the one to any other node until all nodes are visited [26]. For the typical ER random network model shaped by drawing a link between every pair of nodes ($n$ nodes in all) with probability $p(>p_c \propto \ln n/n)$, the topology parameters are as follows.

1）Link to node ratio $R = p(n-1)/2$

2）Degree distribution $F(d) = \binom{n}{d} p^d (1-p)^{n-d} \to \bar{d}^d e^{-\bar{d}} / d!$

3）Mean path length $L \propto \ln n / \ln \bar{d}$

4）Clustering coefficient $C = \bar{d} / n \ll 1$

Where, $\bar{d} = p(n-1) \approx pn$ is the average degree of a random network. Random networks are sometimes referred to as “egalitarian” networks, where degree distribution can be expressed as a normal or “bell” curve, though it is in fact a Poisson distribution but not a skewed one[27]. It is a pity also that these networks are not very efficient, though their mean path length and clustering coefficient are both relatively low. The other drawbacks arise from the random connection of links and nodes: 1) mean path length has a large variation from node to node; 2) there is a large variation in the clustering coefficient. This property changes as the size of the network and the relative density of the interactions between nodes change. It may well take a very large number of steps or linkages to move from one node to another. Irregular path length and clustering therefore cause great unpredictability in networks. Furthermore, removing a modest percentage of the nodes or linkages in a random network will result in splintering into a number of unconnected structures. Hence, they are quite vulnerable to attacks and may degrade quickly if linkages are sparse. As a result, they have relatively little practical utility in C2 network design or implementation, with relatively few clusters formed, little controllability, and little reliability when facing random attacks.

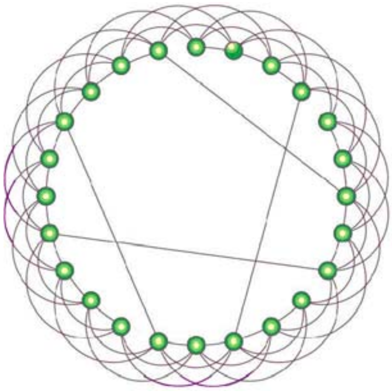
Fig.2 Small World Network

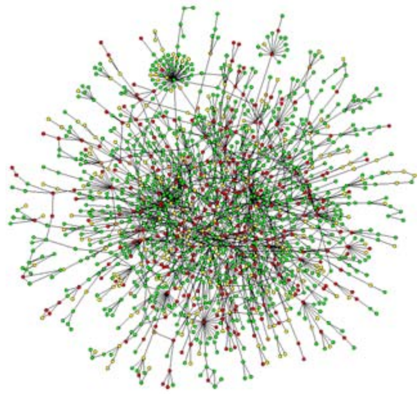
Fig.3 Scale-Free Network

## 3.3 Small World Networks

A small world network (Fig.2) refers to the topology with low mean path length and high clustering coefficient. In a small world network, remote clustered groups share nodes with other remote groups so that the average number of links connecting all nodes remains small. According to the WS model and NW model proposed by Watts el al., minor link rewiring or adding of the nearest-neighbor network can create a small world network that has good clustering and low mean path length [28-30]. Taking WS model for instance: rewiring with probability $p$=1 creates the random network, $p$=0 remains the nearest-neighbor network, and otherwise the small world network, where link to node ratio is identical, and other parameters are given below.

1）Degree distribution

$$F(d)=\begin{cases}\sum_{i=0}^{\min(d-K/2,K/2)}\binom{K/2}{i}(1-p)^i p^{K/2-i}\dfrac{(pK/2)^{d-K/2-i}}{(d-K/2-n)!}e^{-pK/2}, d\ge K/2\\ 0, d<K/2\end{cases}$$

2）Mean path length $L(p)=2n\,\mathrm{f}(nKp/2)$

3）Clustering coefficient $C(p)=3(K-2)(1-p)^3/4(K-1)$

Where, $\mathrm{f}(x)\approx(\arctan\sqrt{x/(x+2)})/2\sqrt{x^2+2x}$ . Small world network is the richest, most efficient class of network currently under study. The distinguishing feature of small world networks, however, is a very large clustering coefficient. As a result, a link to any one node is readily tied to a number of other nodes. As a hastily formed networks arising to deal with the aftermath of a natural disaster or to carry out a specific, temporary military mission, will function relatively efficiently and robustly while needed, then gradually disappear as the interactions become less frequent and the linkages atrophy or are abandoned [20]. The nodes with the relevant knowledge and capabilities in the small network form richly linked and frequently interacting clusters that permit them to exchange information, develop shared situation awareness, and collaborate in order to synchronize their plans and undertake synergistic actions, which contribute greatly to the effect of "power to edge". For a WS small world network with $K$ =4, the link to node ratio is 2, the clustering coefficient is $(1-p)^3/2$, and it can be transformed to be suitable for C2 networks by adjusting $p$. The Achilles' heel of small network is in fact that the degree distribution is similar to random networks, i.e., the degrees of all nodes are mostly close, which results in an impassable barrier.

## 3.4 Scale-Free Networks

A scale-free network model (Fig.3) is introduced by removing two assumptions that once were obstacles to the development of the more advanced network structures: 1) all the nodes in a network should be prescribed before analysis or theoretical investigation began; 2) links were always added according to a fixed distribution. The scale-free network is then created by iteratively attaching each new node to nodes in the network based on the number of links each node already possesses. Technically, this was achieved by weighting the probability that a node is selected by the degree of the node. Founded on the growing characteristic and rich-get-richer scheme, this network has one beneficial property that marks it as a very adaptive network – the degree distribution is represented by a skewed curve. More correctly, scale-free networks have a power law distribution, which makes them extremely robust to random attacks that wipe off a lot of nodes randomly [31-32]. In detail, a scale-free network can be created from a simple network with $n$ nodes: add a new node, and link it to the old $m$ （$<n$) nodes, which is selected based on the probability of their degrees, and while enough nodes are generated and added after $t$ steps, the topology parameters can be calculated according to the formulas below.

1）Link to node ratio $R_t = (nR_0 + mt) / (n+t)$

2）Degree distribution $F(d) = 2m(m+1) / d(d+1)(d+2) \propto 2m^2 d^{-3}$

3）Mean path length $L \propto \ln n / \ln \ln n$

4）Clustering coefficient $C = m^2 (m+1)^2 (\ln((m+1)m^{-1}) - (m+1)^{-1})(\ln t)^2 / 4t(m-1)$

Throughout the scale-free network, a set of dynamic clusters with high clustering coefficient occur naturally. Between these clusters that are connected strongly inside, very long linkages, more or less, may always exist to bridge the gaps and to reduce the number of steps required for an interaction to move from one part of the space to another. Even a few such linkages, provided that they link nodes that serve as hubs for clusters within each region of the network, create a remarkably efficient, resilient and capable network by lowering enormously mean path length [33]. The fact that the mean path length rises in direct ratio to lg($n$)/lg(lg($n$)) proves the small world effect of scale-free networks, where $n$ is the number of nodes. Unfortunately, they have their own weakness, i.e., be vulnerable if one knows how to find the key nodes and the linkages between and among them and be paralysed if one attacks the a few key nodes consciously. Even the congestion control protocols are considered to reallocate the bandwidth among flows whose rates are adjusted when a node is attacked and out of function, and therefore to cut down the probability of cascading breakdown, the real Internet data with the scale-free network models show that the "robust yet fragile" property previously observed in the study of cascading failures in the scale-free networks is still valid in this scenario [34].

In conclusion, all these typical topology models are not very practical to C2 networks. Regular networks cannot meet the topology requirements of C2 networks alone. And that the bell degree distinguishing feature of random networks and small world networks means that the numbers of neighbors of their nodes are mostly quite close and that only few nodes' degrees depart from custom. The fact denies the existence of centers or hubs that truly exist in C2 networks. Owing to the continuously hierarchical structure in C2 networks, one kind of nodes cannot stand for other kinds, which means no certain scale there. So scale-free structure would become one of the principles of C2 network construction, supposed that the frangibility to vicious attacks was reversed.

According to *Understanding Command and Control* by Alberts, the richest and most resilient network structure appears to be a hybrid that looks at the global level like a scale-free networks, but at the intermediate level is composed of small world networks, and at the local level globally coupled networks [20]. This combination seems to provide the blend of efficiency, effectiveness, and resilience needed for large-scale enterprises operating in multi-dimensional, dynamic environments, but the correctness, veracity, and feasibility of this conclusion are waiting for further research and quantified attestation.

# 4 Dilemma and Way out

It seems that networked C2 systems with mobility and dynamic topology support could have longer paths to accommodate information operations, atmospheric conditions, electronic warfare, failed nodes, etc. Now, researches on C2 networks are confronted with the fundamental problems stated hereinafter: 1) How to build a C2 network topology that is efficient, robust, self collaborative and able to curb threats? 2) How to reconstruct a C2 network topology that can be readily accessed anytime and anywhere adaptively? 3) How to assess the network topology accurately? 4) How to achieve topology security and performance guarantees through the built-in mechanism?

The essential issue standing on the way to solving the problems above is lack of theoretical guidance from the topology point of view, which is specifically manifested in the following aspects.

1) There is no pointed theory on topology creation for C2 networks. The existing topology models like regular networks, scale-free networks, small-world networks and random networks mainly model the complexity of the Internet statistically for analysis, and do not have the capability of specification and forecasting for global topology and its evolution. Furthermore, the current organizational structure of C2 network topology presents significant differences from that of the Internet. For example, the role that a node plays in a C2 network may vary with time, while the demands of C2 network in controllability and immediacy are higher than that of other applications So, if topology modeling and theoretical analysis deviate from the characteristics and

needs of C2 networks, the desired flexibility and overall performance will surely be reduced, leading to the high time overhead and cost in building and maintaining a applicable C2 network. Here is a case in point: in the network maintenance process, it takes nearly two months to debug and solve the network congestion and availability issues caused by the dramatic increase of network traffic, because there is no theoretical guidance from related topological performance analysis.

2) The method to support dynamic reconstruction of a desired topology does not exist. A C2 network needs to be running according to specific parameters in real time to carry out the excavation of key nodes and then in accordance with the corresponding topology theory and the performance or security analysis results, the key nodes achieve the migration and self reconstruction and other nodes in their turn. Meanwhile, when achieving the access of mobile nodes to edge networks and the self organization and interconnection of edge networks, the network as a whole achieves load balance, enhancing the overall strengths. For the moment, the academic society and the industrial cycle propose a series of solutions for key technologies, including layered architecture of ad hoc networks, dynamic on-demand routing, and network mobility basic support protocol and so on. However, existing programs are starting from the local problems, and difficult issues are still there, such as large delay, low capability in mobility, security loss. The key point is that a holistic view of the topology of the various particle sizes is not introduced, void of standardized analytical methods like real-time network model of multi-dimensional parameter situation (delay, topology, protocol overhead etc.) and global effects of local topology specification models. For instance, how to sense and self optimize network clustering coefficient and mean path length? Which "shortcut" should be added to effectively reduce the average path length? Which network topology is a useful small world? How to take advantage of the small-world properties? What is the node mobility model and the interconnection models between nodes [35-36]?

3) There is no an effective mechanism for credible topology and a defense method for secure topology. Under network environment, the credibility is dynamic, transferable, and inevitably the phenomenon of entropy increase happens, while the C2 networks allege real-time and high determinacy. Credibility of the current networks relies on the high-level authentication based on user identity or a subjective assessment of the credible probability based on observation and trust transfer. The inflexibility of the former and the uncertainty of the latter are fatal to C2 networks. At the same time, due to the universality of platform vulnerability, the attacks and computer viruses spread like wildfire, and that some remedial measures such as firewall, anti-virus software and intrusion detection system are aimed at the border. But many issues are in the air still: how to effectively distinguish the external and the internal among systems or users? If topology can evolve its own structure directly rather than depend on the external remedial measures to address security issues?

4) The C2 network is lack of an effective topology model for performance guarantee. A C2 network should adaptively control the performance of interaction, according to service requests of nodes, rights of users, and network traffic, such as end to end bandwidth, delay, jitter, packet loss and other services. Currently, the mechanisms attached for quality of service are mainly based on the resource reservation model or pre-defined priority model. The former needs to apply for registration at remote places, experiencing a larger delay, and resulting in less scalability, the latter with coarse control granularity is not flexible. Moreover, since interoperability is absent between

those control mechanisms, inter-domain cooperation for quality of service and overall performance is very difficult. And, that if topology can solve this problem by adjusting its own structure to produce small-world remains to be further theoretical analysis.

So, the current way should start from the structure and dynamics, the essentials of C2 network topology, and carry out the following work to prove the accuracy and validity of the hybrid networks, an ideal model proposed by Alberts, and to build and maintain the desired one.

1) Characterization of C2 topology

The existing topology theories are based on dual structure, i.e., node and link, which can not fully reflect the structure and dynamics of behavior formed by multiple levels of interaction of links, information, command and coordination, resulting in coarse quantitative granularity of characteristics in C2 topology requirements analysis. Description method of C2 network topology is urgent to be studied to reflect accurately the full characteristics.

2) Properties of C2 topology

At present, the main sticking point for mathematically modeling of C2 network topology is unable to establish the mapping between the specific elements of the physical characteristics of the topology needs and quantitative description of topological attributes. That is to say, here is only the need to achieve qualitative objectives, without the quantitative indicators corresponding to these objectives. Therefore, detailed physical features like security, survivability, efficiency, and others are to be quantified, figuring out the internal principles of topology.

3) Model resolution and C2 topology construction

The purpose of topology modeling is to provide a theoretical basis of generating the optimal form of C2 network topology, but the model resolution becomes a new problem after creating the mathematical model in accordance with the needs of specific tasks and topology properties. Since topology model varies with application requirements, studying the general ideas of topology model resolution and of generating optimal topology shapes great value in the future.

4) Evolutionary mechanisms of C2 topology

After C2 topology is constructed, evolution becomes the principal problem. As the topology evolution affected by not only many factors, including those in physical domain, information field, and social domain, but also a variety of factors interacted with each other with changes in environment and tasks, the complex dynamics related closely with the topology structure comes into being. Therefore, it is vital to study the rational dynamics for topology evolution, through the adaptive adjustment of the system structure and key protection, converging quickly to meet the needs of the C2 network security level and performance status, and maintaining stability.

The work on C2 network topology is still in its infancy at present. Although there are some fruits, many problems still remain to be cracked. The key technologies of answering these problems constitute the future direction and rich contents, which are closely related, promoted step by step, composing an indivisible whole in the field of command and control.

# 5 Conclusions

For the moment, the researches on complex networks are absolutely on the rise, which, from the statistics aspect, turns on a new light for topology study. Nevertheless, the existing network models aimed mostly at the Internet that is simply duality topology with loose structure, focusing primarily on the modeling and evolution analysis of the Internet's local features. But C2 networks need global management and real-time control with high survivability and central administration, where the factors that influence significantly the C2 topology are more complicated. Thus, existing network topology theories fail to deal with topology modeling and quantitative analysis of C2 network. There is generally no gauge theory for topology control and optimization of C2 network. Future work on precise description, quantified requirements and attestation, model resolution, construction and evolution of topology is eager for opening out earnestly, as mentioned in part 4. This paper surveys the related works, topology requirements and statistical metrics of C2 networks, points out the problems ahead and the way out after analysis of typical network model.

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