Research and Construction Model of Cyberspace Based on Hypergraph

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Keywords: Cyberspace Model, Hypergraph Theory, Multilayer Relationship

Abstract. With the increasing number of cyber incidents currently, cyberspace has become a more and more important domain. Lack of suitable models to characterize cyberspace makes it hard to carry on researches in this area. This paper presents a novel cyberspace model based on hypergraph to describe homogeneous and heterogeneous entities interacting through complex relationships in multi-layer cyberspace. By decomposition of proposed hypergraph model into sub-hypergraphs, we described multi-layers and relationships in cyberspace.

1. Introduction

At present, some works have mainly been carried out to study cyberspace framework and structure. Literature [1], [2]and [3] analyzed etymology of "Cyberspace" and some basic structures of cyberspace were given. The US Department divided cyberspace into three layers (physical, logical and social) including five components (geographic, physical network, logical network, persona and cyber persona)[3][4][5]. Jakobson[6] and Barnett[7][8] modeled cyberspace from hierarchical aspects and regard mission as a layer within cyberspace. Although frameworks mentioned above provide beneficial thoughts, current study still can not meet the requirement of quantitative description. Cyberspace modeling faces the following challenges:

(1) Terrain map technique has gained great remarkable achievements for physics space modeling, but fundamental differences exist between cyberspace and traditional physical domain or simple computer network and this technique is no longer applicable for cyberspace modeling. Different from the physics space, cyberspace is not only a material space composed by numerous network infrastructures, but also a mission space that support user behavior and cyber missions.

(2) Graph-theoretic approach has gained tremendous benefits in internet modeling. However, a graph can only capture binary relations between homogeneous entities[8], it is not able to distinguish between heterogeneous entities and different types of entity relationships in cyberspace. Cyberspace covers from network equipment, physical environment, to people and organization. Various and distributed entity resources connect by complex interactive relationship including intra dependencies among the same layer and inter dependencies between different layers[9].

Hypergraph is a generalization of graph theory proposed by Berge[10] designed to represent a set of subsets on a finite set. It has been applied for domains where multilevel structure relations with dynamics such as co-authorship exist[11] and robot-robot interactions[12]. We propose to employ hypergraph to exploit the multi-layer relations among homogeneous entities and heterogeneous entities in cyberspace.

It is essential that a model accurately and abstractly depict widely recognized entities and layers in cybersapce. But how to map homogeneous and heterogeneous entities intertwine in a mess into a hypergraph? Cyber incidents happening everyday give us an indication to build cyberspace model from cyber events perspective. Various entities from different layers involved in cyber events are treated as attributes of events and cyber events are represented as nodes. A node in a hypergraph can be contained by multiple hyper-edges which represent a cyber event which has more than one attribute.

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2. Cyberspace Model Based on Hypergraph

2.1 Theoretical Foundation

As an extend of graph, a hypergraph H is defined as:

$$H = (V, E) \tag{1}$$

$$V = \{v_1, v_2, ..., v_n\}\ ,\quad E = \{E_1, E_2, ...E_m\} \tag{2}$$

$$E_i \neq \varnothing \text{ and } \bigcup_i E_i = V \tag{3}$$

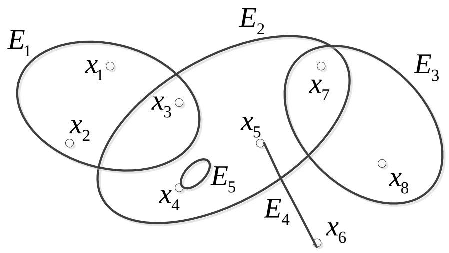

Figure 1: An illustration of hypergraph

Different from traditional graph, a hyper-edge E_i in hypergraph is a subset of V, as illustrated in Figure 1. In the case that each hyper-edge only include only two nodes, hypergraph becomes a simple graph. A hypergraph becomes a $n \times m$ adjacency matrix $E(H)$ if we correspond nodes and hyper-edges, represented as:

$$E(H) = \left[e_{ij}\right]\ ,\quad e_{ij} \in \{0,1\} \tag{4}$$

Value e_{ij} indicates relationship between the i th node and j th hyper-edge, where $e_{ij} = 1$ if $v_i \in E_j$ and $e_{ij} = 0$ if $v_i \notin E_j$. Deriving from Graph theory and Set theory, hypergraph has gained distinct advantage in describing multi-layer and multi-dimension network problems and we model cyberspace base on it.

2.2 Composition of Cyberspace Hypergraph

According to hypergraph theory, nodes in common set from layer N can be assembled as a new node at Layer N+1[12], as illustrated in Figure 2.

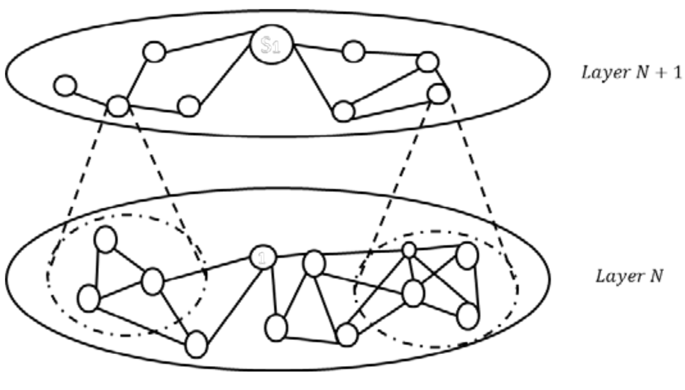

Figure 2: Entities in common set from layer N can be assembled as a new node at Layer N+1

In cyberspace cyber missions are composed of concurrent or cooperative services and services exert their function depend on assets. Assets, services and missions are considered as entities of cyberspace and each of them can form a cyber layer. Jakobson et al. put forward a multi-layer framework in which they framed cyberspace from three dimensions including asset-layer, service-layer and mission-layer[6], as shown in figure 3. In our model,we compress multi-layers in this framwork into a hypergraph. Various entities from different layers involved in cyber events are treated as attributes of cyber events and they are represented as nodes in cyberspace model.

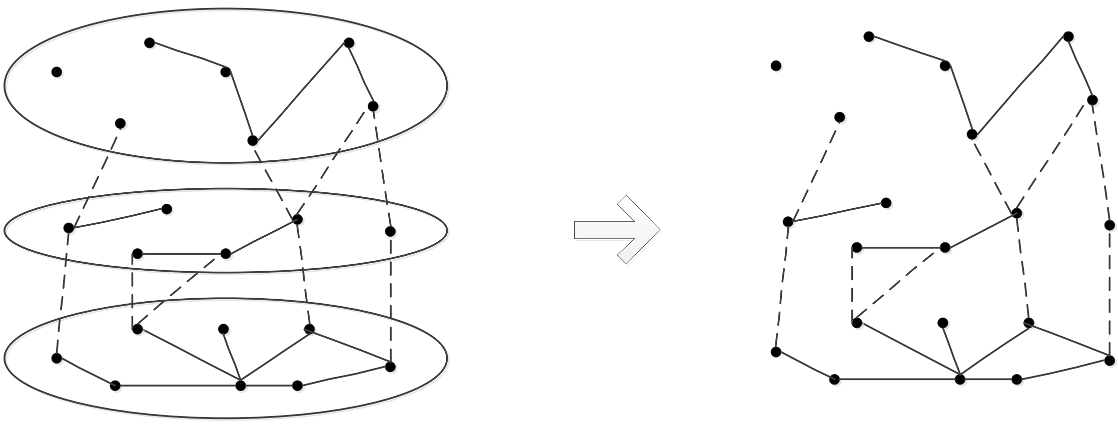

Figure 3: Composition of event attributes as a node in hypergraph

Based on theory put forward in section 2.1, we described the cyberspace as a hypergraph:

$$H=(V,E) \tag{5}$$

(1) $V=\{v_1,v_2,v_3,...\}$ represents events happened in cyberspace and each node contains an attribute set as an event is characterized by some key elements, as shown in Figure 3.

$$v_i=<v_{i\_a},v_{i\_s},<v_{i\_m1},v_{i\_m2},v_{i\_m3},...>> \tag{6}$$

Where,

1) i represents the i th event;

2) v_{i_a} is the asset attribute indicating a physical environment such as cyber hardware or software. We give serial number for each asset, form set $A=\{a_1,a_2,a_2,...,,a_x\}$;

3) v_{i_s} represents service attribute of a cyber event and service set can be $S=\{s_1,s_2,s_3,...,,s_y\}$;

4) v_{i_mj} represents that the j_{th} mission is impacted in event i In high-coupled cyberspace, an event often concerns more than one mission. Mission attribute indicate missions involved by events and its set can be $M=\{m_1,m_2,m_3,...,m_z\}$.

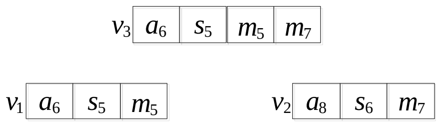

Figure 4: Event nodes in cyberspace hypergraph

(2) Edge set $E=\{E_A,E_S,E_M\}$ is a hyper-edge set and each element contains nodes with a same attribute. E_A , E_S and E_M represent relathionship between homogeneous entities. Illustration of hyper-edge set will be given soon afterwards.

3. Decomposition of Cyberspace Model

3.1 Sub-Hypergraphs Represent Multi-layers

Including different critical infrastructure networks, cyberspace is a multi-layer network of network [8]. Through decomposition, cyberspace model can uniformly describe homogeneous and heterogeneous entities interacting with their complex relationships in multi-layer cyberspace. Relationships among attributes of cyber events stand for inter and intra dependencies of entities. We respectively frame the asset sub hypergraph (ASH), service sub hypergraph (SSH) and mission sub hypergraph (MSH) according to definition of hyper-edge of the cyberspace hypergraph to describe intra- relation between homogeneous entities from one layer and inter- relation between heterogeneous entities from different layers.

i) ASH

In ASH, we consider cyber events that have common asset attribute as a hyper-edge, represented as E_{Ai} in equations as follows.

$$H_A = (V, E_A) \tag{7}$$

$$E_A = \{E_{A1}, E_{A2}, E_{A3}, ... E_{Ax}\} \tag{8}$$

$$E_{Ai} = \{v_i \mid v_{i\_a} = a_i, v_i \in V, a_i \in A\} \tag{9}$$

An aggregated set represent a cyber asset entity. If connected by physical electric circuit, cyber assets will form the asset layer. Shown as Figure 5.(A).

ii) SSH

If hyper-edge is defined as set of cyber events with the same service attribute, represented as E_{Si} in equations as follows, then aggregated events will form entities of service layer. Relationship of service entities can be logical connection. Shown as Figure 5.(B)

$$H_S = (V, E_S) \tag{10}$$

$$E_S = \{E_{S1}, E_{S2}, E_{S3}, ... E_{Sy}\} \tag{11}$$

$$E_{Si} = \{v_i \mid v_{i\_s} = s_i, v_i \in V, s_i \in S\} \tag{12}$$

iii) MSH

Similarly, the MSH derivates from the premise that we define hyper-edge as set of cyber events that have the same mission attribute, represented as E_{Mi} in equations as follows. Mission layer of cyberspace is then formed by interoperability between missions. Shown as Figure 5.(C)

$$H_M = (V, E_M) \tag{13}$$

$$E_M = \{E_{M1}, E_{M2}, E_{M3}, ... E_{Mz}\} \tag{14}$$

$$E_{Mi} = \{v_j \mid v_{j\_m_i} = 1, v_j \in V, m_i \in M\} \tag{15}$$

Furthermore, we describe the ASH, SSH and MSH with matrix language $E(H)$:

$$E(H) = \begin{array}{c} \\ v_1 \\ v_2 \\ \cdots \\ v_i \end{array} \begin{array}{c} \begin{array}{ccc} E_1 & E_2 ... & E_j \end{array} \\ \begin{bmatrix} 0 & 1 & 1 \\ 1 & ... & 1 \\ ... & ... & ... \\ 0 & 1 & 0 \end{bmatrix} \end{array} \tag{16}$$

Elements in $E(H)$ represent correspondences between cyber events and entities of cyber layers. Then we get $E(H_A)$, $E(H_S)$ and $E(H_M)$, respectively describes the ASH, SSH and MSH.

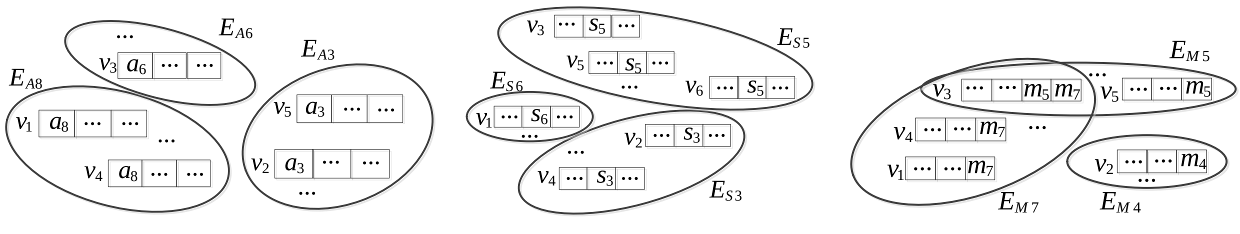

Figure 5: Event nodes in cyberspace hypergraph

3.2 Relationship Between Sub-Hypergraphs

In cyberspace, relationships include not only intra-relation between homogeneous entities, but also inter- relation between heterogeneous entities. Entities from different layer of cyberspace often interact with each and collaboratively impact mission operating. For example, an event happens about service s_j on asset a_i and impact mission m_k, m_m and m_n, then a hypergraph node is represented as: $v_i = < v_{i\_a}, v_{i\_s}, < v_{i\_m1}, v_{i\_m2}, v_{i\_m3}, ... >>$. Entity s_j in service layer depend on entity a_i in asset layer and s_j support entities m_k, m_m and m_n in mission layer. Translating inter- relation between heterogeneous entities into matrix language, we get $E(H_{A-S})$, $E(H_{S-M})$ and $E(H_{A-M})$, respectively represent relationships between entities from asset layer and service layer, service layer and mission as well as asset layer and mission layer. As an example, $E(H_{A-S})$ is expressed as:

$$E(H_{A-S}) = \begin{array}{c} \\ a_1 \\ a_2 \\ \ldots \\ a_x \end{array}\begin{array}{c} \begin{array}{ccc} s_1 & s_2 \ldots & s_y \end{array} \\ \begin{bmatrix} 3 & 1 & 2 \\ 3 & \ldots & 1 \\ \ldots & \ldots & \ldots \\ 0 & 5 & 0 \end{bmatrix} \end{array} \tag{17}$$

Where, element $e_{(A-S)ij}$ in matrix $E(H_{A-S})$ represents correspondence between assets and services. If $e_{(A-S)ij} \neq 0$, asset a_i relates with service s_j. Value of $e_{(A-S)ij}$ indicates relativity intension. Instance that two entities in one layer together depend on another entity in other layer is expressed by adjacency matrix:

$$A(H) = EE^T - D \tag{18}$$

4. Conclusion and Future Work

This paper provided a novel method for cyberspace modeling. By composition of cyberspace framework, we mapped homogeneous and heterogeneous entities into a hypergraph. By decomposition of hypergraph, we described multi-layers and relationships including intra-relation between homogeneous entities and inter- relation between heterogeneous entities. The ASH, SSH and MSH respectively depict relationships among assets, services and missions.

Although we proposed a solution for cyberspace modeling in this study, following issues still needed further researches. Entities a cyber event concerns may be countless, we only considered about asset entities, service entities and mission entities. What's more, collecting cyber events is not easy, an automatic framework including sensors, intrusion detection mechanism and statistic analysis will be further studied.

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