Importance Evaluation of C^4ISR Communication Nodes Based on Multi-attribute Decision-making

Fangsheng Li, Jianfeng Hou*, Lianzheng Qu and Binbin Fan
Dept. of Info. Communication, National Univ. of Defense Tech, Wuhan, China

* Corresponding author e-mail: h8jj4f@126.com

Abstract. Node importance is a key measuring index for network structure characteristics. Evaluating the nodes importance can locate key nodes of the network and provide support for network node planning. The importance of the C^4ISR communication node reflects the dependence degree of the functional nodes and functional links on the C^4ISR transport nodes. How to transform this qualitative dependence into quantitative dependency measuring is the core problem of evaluating node importance and locating key nodes. Based on the quantitative dependence measuring, this paper proposes a C^4ISR communication node importance evaluation method based on multi-attribute decision-making. Meanwhile, the applicability of the method is verified by examples.

1. Introduction

At present, there are lots of research results on node importance evaluation. Among them, node importance definition and measurement are two main research contents [1]. The network node importance metric is a quantitative index of the network node importance. Selecting the scientific and reasonable network node importance metric is the premise of the network node importance evaluation [2]. Currently, from the perspective of network science, related indexes mainly include degree centrality, constraint, and closeness centrality. These metric indexes describe the significance of nodes in the network from different aspects [3][4].

Most of the existing definitions and measurement studies on the importance of network nodes focus on the connectivity of nodes in the topology, and do not consider the functional role of nodes in specific network environments [5]. However, C^4ISR is a functional network with a special application environment. Directly using the existing node importance metrics based on complex network to evaluate the node C^4ISR node importance cannot accurately solve the actual importance evaluation problem.

2. An integrated multi-attribute C^4ISR node importance evaluation method

To evaluate the node importance of C^4ISR, the impact of heterogeneous functional nodes and functional links on the network should be considered.

2.1. Related concepts

The information flow direction, path and sequence of C^4ISR conforms to the basic rules of operational command. A complete process ranging from information obtaining to the final generation forms a “network chain”. A large number of “network chains” in C^4ISR contribute to the overall realization of operational function. Based on this, the paper gives the definition of C^4ISR node
importance: with the traction of operation requirements, the critical degree of C4ISR transmission node playing a role in the process of each entity of the operation system relying on C4ISR to build the information link and form the combat function.

2.2. Related measures

In C4ISR, the theoretical maximum number of links should be determined in conjunction with the number of edge functional nodes, and should not be the full number of connections for all nodes. Based on this, the paper optimizes the existing algorithm of node importance degree measure to enhance the applicability of the measure index. The degree centrality and the constraint are measures of the local structural features of the network, not involving the network edge function nodes, and the algorithm remains unchanged. Nevertheless closeness centrality and betweenness centrality are measures of the whole structural characteristics of the network, involving the edge functional nodes of the network. And its algorithm is quite different from the node importance measure algorithm given above.

The C4ISR node centrality is represented by the reciprocal of the average distance between node and all edge function users, namely: $V_2 = N / \sum_{j=1}^{N} d_{ij}$, in the formula, $d_{ij}$ indicates the distance between the transmission network point $i$ and the edge function user $j$.

The C4ISR betweenness centrality is expressed as the ratio of the shortest path number through the node to the shortest path number among the edge function users, namely: $V_4 = \sum_{i,j,k} g_{jk}(i) / g_{jk}$, in the formula, $g_{jk}(i)$ represents the number of the shortest paths between the edge function user $j$ and the edge function user $k$, and $g_{jk}$ represents the number of the shortest paths passing through network transmission point $i$ between the edge function user $j$ and the edge function user $k$.

2.3. Evaluation method

To fully reflect the functional characteristics of the combat network, this paper treats the network terminal users as various functional nodes, and incorporates them into the network topology nodes to comprehensively evaluate the importance of the transmission nodes. These functional nodes are at the edge of the network and are also the origin or destination of the information in the network.

The figure $H = \{V, E, V^*, E^*\}$ represents a C4ISR considering the combat function, and $V = \{S, P, U, E, T\}$ represents a set of nodes, among which $S = \{s_1, s_2, \ldots, s_u\}$, $P = \{p_1, p_2, \ldots, p_v\}$, $U = \{u_1, u_2, \ldots, u_l\}$, $E = \{e_1, e_2, \ldots, e_r\}$ and $T = \{t_1, t_2, \ldots, t_k\}$, respectively representing information collection, information processing, information usage, information efficiency, and information transmission node set. The number of various nodes is respectively represented by $M$, $N$, $I$, $J$ and $K$, with $|V| = M + N + I + J + K$. And $V^* = \{V_1, V_2, \ldots, V_k\}$ represents the node importance attribute set.

Setting the number of function nodes as $F$, then the network adjacency matrix $H = [h_{ij}]$ has $K + F$ rows and $K + F$ columns. Setting the comprehensive evaluation value of the network transmission nodes as $X$, then the evaluation value of each transmission node can be represented as $X = \{X_1, X_2, \ldots, X_k\}$. Setting there are $R$ importance evaluation indexes of a single transmission node, then the corresponding transmission node importance attribute set can be expressed as $V^* = \{V_1, V_2, \ldots, V_k\}$. Then, the $j$ importance index of the $i$ transmission node in the network can be expressed as $X_i(V_j)$, among which $i = 1, 2, \ldots, K$, $j = 1, 2, \ldots, R$. Based on the above, the transmission node importance evaluation matrix of the network can be expressed as:

2
There are a few node importance metric indexes and each has their own emphasis, and they also have more or less relationships. Some indexes are beneficial, the larger the value is, the more important the nodes are. While some indexes are costing, the smaller the value is, the more important the nodes are. Therefore, the evaluation matrix needs to have chemotaxis processing:

\[
    z_j = \begin{cases} 
    \frac{X_i(V_j)}{X_i(V_j)}_{\text{max}} & \text{if the indexes are beneficial} \\
    \frac{X_i(V_j)}{X_i(V_j)}_{\text{min}} & \text{if the indexes are costing}
\end{cases}
\]

After chemotaxis processing, the node importance evaluation matrix can be expressed as:

\[
    Z = (z_j)_{K \times R}
\]

Set the weight of \( j \) node importance evaluation index as \( w_j \) (\( j = 1, 2, \ldots, R \)), \( \sum w_j = 1 \), then the weighted node importance evaluation matrix can be expressed as:

\[
    Y = (y_j) = (w_j z_j) = \begin{bmatrix} 
    w_1 z_{1j} & \cdots & w_R z_{Rj} \\ 
    \vdots & \ddots & \vdots \\ 
    w_1 z_{1j} & \cdots & w_R z_{Rj}
\end{bmatrix}
\]

Suppose there are two reference nodes, the most important node and the least important node, and the evaluation values are respectively \( X^+ \) and \( X^- \), and the importance of the node is quantitatively represented by calculating the distance between the actually existing nodes and the two reference nodes. \( X^+ \) and \( X^- \) can be respectively expressed as:

\[
    X^+ = \left\{ \max_{i \in R} (y_{i1}, y_{i2}, \ldots, y_{ia}) \right\} = \{ y_1^{\text{max}}, y_2^{\text{max}}, \ldots, y_R^{\text{max}} \}
\]

\[
    X^- = \left\{ \min_{i \in R} (y_{i1}, y_{i2}, \ldots, y_{ia}) \right\} = \{ y_1^{\text{min}}, y_2^{\text{min}}, \ldots, y_R^{\text{min}} \}
\]

The distance between the node \( i \) and the two reference nodes are respectively set as \( D_i^+ \) and \( D_i^- \), which can be respectively expressed as:

\[
    D_i^+ = \left[ \sum_{j=1}^{R} (y_{ij} - y_{j}^{\text{max}})^2 \right]^{1/2}
\]

\[
    D_i^- = \left[ \sum_{j=1}^{R} (y_{ij} - y_{j}^{\text{min}})^2 \right]^{1/2}
\]

Based on the above, the comprehensive evaluation index \( C_i^* \) of the node \( i \) can be obtained:

\[
    C_i^* = D_i^- / (D_i^+ + D_i^-)
\]

3. Evaluation sample

In this section, based on constructing the typical C^4ISR topology, the importance of the C^4ISR nodes is solved.

3.1. Typical C^4ISR functional structure construction

Figure 1 is a typical topological structure that reflects the heterogeneous and functional properties of nodes in C^4ISR. From the perspective of the overall topology, the network is divided into three parts: core, access and application. From the perspective of node connection, C^4ISR has a grid topology. From the perspective of the node attribute, according to the purpose, the nodes can be divided into functional nodes and transmission nodes, wherein the functional nodes are further divided into information sampling nodes (S), information processing nodes (P), information using nodes (U), and information Efficiency nodes (E). While from the perspective of the link attribute, combining information communication requirements, a variety of information function links can be formed...
among different functional nodes. In addition, as the information source and the information receiver, the information collecting node (S) and the information efficiency node (E) access the core network from different access nodes. The processing node (P) and the using node (U) may be connected to the core network through the access nodes, or may be directly connected to the core network through the backbone nodes.

![Diagram of different functional nodes](image)

**Figure 1.** C4ISR Function structure.

### 3.2. Evaluation of the C4ISR nodes importance considering node heterogeneity

In this section, under the 2 circumstances of considering and not considering the edge function nodes, the Pajek topology analysis tool\[^6\] is used to evaluate the four importance metric indexes of the C4ISR transmission node, which are degree centrality, closeness centrality, constraint, and betweenness centrality. Meanwhile, using the multi-attribute decision making method, the importance considering the edge function nodes is comprehensively evaluated.

![Network topology diagram of non-edge function nodes](image)

**Figure 2.** Network topology diagram of non-edge function nodes.

Figure 2 is a network topology diagram of non-edge function nodes. The number of nodes is 18. At this time, the access network node becomes the edge node of the network topology. Respectively combining the formulas, the four types of importance metric indexes of all nodes can be calculated, as shown in Table 1.

| Index                  | V1    | V2    | V3    | V4    | V5    | V6    | …   |
|------------------------|-------|-------|-------|-------|-------|-------|-----|
| Degree centrality      | 4.0000| 6.0000| 4.0000| 4.0000| 4.0000| 4.0000| …   |
| Closeness centrality   | 0.4474| 0.5313| 0.4474| 0.4250| 0.5000| 0.4250| …   |
| Constraint             | 0.2500| 0.1667| 0.2500| 0.2500| 0.2500| 0.2500| …   |
| Betweenness centrality | 0.2941| 0.5294| 0.2941| 0.2721| 0.3603| 0.2721| …   |

**Table 1.** Importance evaluation value of non-edge function nodes.
Figure 3 is a network topology diagram having the edge function nodes. The number of nodes is 61. At this time, the closeness centrality is defined as the reciprocal of the average distance between the transmission nodes and all other edge functional nodes. The betweenness centrality is defined as the ratio of the number of the shortest paths among the functional nodes passing through the transmission node to the number of the shortest paths among all functional nodes in the network.

![Network topology diagram having edge function nodes.](image)

Combined with the formulas (1), (2), the importance evaluation values of the network transmission nodes adding the edge function nodes can be obtained by calculation, as shown in Table 2. For this paper mainly studies the influence of edge function nodes on the importance of transmission nodes, so only the evaluation values of 18 transmission nodes are selected as samples.

| Index                | V1   | V2   | V3   | V4   | V5   | V6   | ...
|----------------------|------|------|------|------|------|------|------
| Degree centrality    | 4.0000 | 6.0000 | 6.0000 | 4.0000 | 4.0000 | 4.0000 | ...
| Closeness centrality | 0.3315 | 0.3797 | 0.3315 | 0.3093 | 0.3509 | 0.3093 | ...
| Constraint           | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | ...
| Betweenness centrality | 0.3299 | 0.5943 | 0.3518 | 0.2783 | 0.3680 | 0.2568 | ...

For the closeness centrality, the importance index having global attributes, in the case of non-edge function nodes, it can be expressed as $V_i = 18 / \sum_{j=1}^{18} d_{ij}$. While when adding edge function nodes, it can be expressed as $V'_i = (18 + 43) / \sum_{j=43}^{61} d_{ij}$. By calculation, it can be found that in the case of considering only edge function nodes, the expression is $V'_i = 43 / (18/V_i + 61/V'_i)$.

When considering only the edge function nodes, the evaluation values of closeness centrality and Betweenness centrality are shown in Table 3.

| Index                | V1   | V2   | V3   | V4   | V5   | V6   | ...
|----------------------|------|------|------|------|------|------|------
| Degree centrality    | 4.0000 | 6.0000 | 6.0000 | 4.0000 | 4.0000 | 4.0000 | ...
| Closeness centrality | 0.1918 | 0.2210 | 0.1918 | 0.1795 | 0.2049 | 0.1795 | ...
| Constraint           | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | ...
| Betweenness centrality | 0.3332 | 0.6002 | 0.3571 | 0.2789 | 0.3687 | 0.2554 | ...

Table 2. Importance evaluation value having the edge function nodes.

Table 3. The importance evaluation value only considering the edge function nodes.
According to formula (5) and (6), by calculation the positive reference node and the negative reference node can be obtained. At this point, the most important possible nodes and the least important possible nodes are:

\[
X^+ = \{0.2073, 0.2073, 0.0861, 0.2772\}
\]

\[
X^- = \{0.1037, 0.1291, 0.0861, 0.0600\}
\]

According to formula (7) and (8), the distance of \(D_i^+\) and \(D_i^-\) separately from the importance evaluation value of the node \(i\) to the positive reference node and the negative reference node can be calculated. By formula (9), the comprehensive evaluation index \(C_i^*\) of each node \(i\) can be calculated. The three types of index values are shown in Table 4.

**Table 4.** Results of node importance evaluation integrating multiple attributes.

| Index | V1   | V2   | V3   | V4   | V5   | V6   | …   |
|-------|------|------|------|------|------|------|-----|
| \(D_i^+\) | 0.2342 | 0.0000 | 0.2041 | 0.2788 | 0.2052 | 0.2976 | …   |
| \(D_i^-\) | 0.2257 | 0.4581 | 0.2637 | 0.1798 | 0.2570 | 0.1612 | …   |
| \(C_i^*\) | 0.4908 | 1.0000 | 0.5637 | 0.3921 | 0.5561 | 0.3514 | …   |

From Table 4, it can be found that the sequence of node comprehensive evaluation index \(C_i^*\) is:

\[V2>V3>V5>V1>V4>V6>V10>V16>V9>(V8=V13)>V14>V11>V7>V18>V12>V17>V15.\]

4. Conclusion

From the ranking of the importance of the nodes, the following conclusions can be drawn:

1. V2, V3, V5, V1, V4, and V6 are core nodes, and V10, V16, V9, V8, V13, V14, V11, V7, V18, V12, V17, and V15 are access nodes. According to the importance ranking of nodes, it can be known that the core nodes are more important than the access nodes.

2. As the same core nodes, the importance of V2 is better than V3 and V1, and the importance of V5 is better than V4 and V6. In the core network, the degree of V2 and V5 is 3, and the degree of V3, V1, V4, and V6 is 2, which indicates that the nodes with a high degree are more important than the nodes with lower degree (The number of connections with other backbone nodes is small).

3. As the same core node, the topological position of V2 and V5 is similar. The number of access nodes of V2 is 3, while the number of access nodes of V5 is 1. Apparently the importance of V2 is much higher than V5, which indicates among the edge nodes in the core network, the backbone nodes with more access node connections are more important.

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