Influential Nodes Analysis Method of Tactical Mobile Ad Hoc Networks Based on Impact Factors Evaluation

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Abstract. How to identify and analyze influential nodes of Tactical Mobile Ad Hoc Networks is an urgent problem. Existing researches fail to make full use of features of Tactical Mobile Ad Hoc Networks. In this paper, we propose an influential nodes analysis method of Tactical Mobile Ad Hoc Networks based on impact factors evaluation (TINE). The method evaluates node importance through two mechanisms: connectivity analysis and node importance evaluation. In connectivity analysis, the current network topology is reconstructed by placing nodes to monitor network data packets and resolve protocol. In node importance evaluation, node importance degree is calculated by adjacency matrix. The experimental results show that TINE we proposed has advantages over the existing methods in Tactical Mobile Ad Hoc Networks.

1. Introduction

1.1. Tactical Mobile Ad Hoc Networks
Tactical Mobile Ad Hoc Networks is a kind of wireless network with non-center, self-organization and multi-hop sharing. It has the characteristics of no need to set up network infrastructure, dynamic topology and deployed in the forward battlefield area [1]. Communication equipment of Tactical Mobile Ad Hoc Networks is called tactical radio, which uses a consistent battlefield communication network protocol. A typical example is the tactical radio system with primary and secondary battlefield radio networks. Primary battlefield radio is the backbone network and is responsible for data exchange with secondary battlefield radio, such as Enhanced Position Location Reporting System (EPLRS) radio. Secondary battlefield radio is mainly used to ensure the voice and data communication of the following users, such as Single Channel Ground and Airborne Radio System (SINCGARS) radio.

1.2. Influential Nodes Analysis
In complex networks of various fields, influential nodes refer to one or some nodes that have an important impact on the structural characteristics and stability of the entire network. These nodes have a great degree of connection or have a significant advantage in location. The identification and analysis of influential nodes have important application value in the field of military information. On the one hand, the network maintainer can dynamically adjust the information processing ability of influential nodes,
or enhance the communication network security through detecting these nodes; On the other hand, after identifying influential nodes through technical means, the scout can accurately attack the opponent’s network or even destroy it.

1.3. Existing Researches

The most research on the importance of nodes mainly focuses on complex network theory [2]. They can be divided into two categories: system science method and characteristic parameter method. The core of system science method is to measure node importance by its destructiveness to the whole network after deleting it. The node detection and network connectivity (DNC) [3] method use this idea. Although DNC reduces time complexity in its identifying algorithm, it does not combine actual traffic flow as an important index, so it is only applicable to general complex network. The core of characteristic parameter method is to measure node centrality index, such as semi-local centrality (SLC) [4] method and node closeness centrality (NCC) [5] method, the analysis results of these methods are not general in some cases. Aiming at solving these problems, this paper proposed a new influential nodes analysis method of Tactical Mobile Ad Hoc Networks based on impact factors evaluation (TINE). In the experimental part, we use NS3 platform to compare the TINE method with other three major traditional method.

2. Influential Nodes Analysis of Tactical Mobile Ad Hoc Networks Based on Impact Factors Evaluation

The TINE method includes two major mechanisms: connectivity analysis and node importance evaluation. Figure 1 shows the general process of TINE method. Connectivity analysis mechanism includes some steps of setting scenarios, building the tactical network model and using monitoring technical means to reconstruct the opponent’s topology. In node importance evaluation mechanism, shortest routing hops matrix is first calculated from adjacency matrix, then node density centrality is defined, node traffic flow is counted and finally node importance degree is calculated and evaluated.

![Figure 1. The general process of TINE method](image)

2.1. Connectivity Analysis

2.1.1. Scenario description. N primary battlefield radio nodes are initialized to form a primary cluster, in which each secondary cluster contains l secondary battlefield radio nodes and one primary battlefield radio node as the cluster head. In order to ensure that all the battlefield radio nodes are within their maximum communication range, and to meet the requirement of maximum number of routing hops
supported by Tactical Mobile Ad Hoc Mobile Networks, the geographical locations of the two types of battlefield radio need to be constrained.

Set the maximum communication range of secondary battlefield radio node to $RS_{\text{max}}$, the maximum communication range of primary battlefield radio node to $RE_{\text{max}}$, the distance between adjacent secondary battlefield radio node to $S_L$, the distance between adjacent primary battlefield radio node to $E_L$. Then meet the following formula:

$$L_S \leq RS_{\text{max}} \quad (1)$$

$$L_E \leq RE_{\text{max}} \quad (2)$$

2.1.2. Data monitoring process. $s$ monitoring nodes are arranged according to the network size, and the maximum detecting range of each monitoring node is set as $RL_{\text{max}}$. The monitoring nodes are randomly distributed in the whole network, they collect and analyze the communication information by actively monitoring data packets.

Each monitoring node is equipped with an internal listening timer, which can collect network data packets within a specified time. The value of the listening timer is set to $T_{\text{max}}$. Once the listening timer starts, monitoring node will switch to promiscuous model to capture all the data frame sent, received or forwarded by battlefield radio nodes within the maximum detecting range. All the monitoring nodes need to parse protocol (exclusive protocol of Tactical Mobile Ad Hoc Networks, e.g. MIL-STD-188-220D) information of Intranet header. Figure 2 shows the format of Intranet header of MIL-STD-188-220D protocol. Monitoring nodes then extract and filter the originator address, relay address and destination address of each piece of data from the Intranet header to make a complete routing path and finally add it to the connectivity information recording table.

Figure 2. The format of Intranet header of MIL-STD-188-220D protocol

The adjacent monitoring nodes periodically exchange their connectivity information recording table during the time of connectivity information update timer. The value of connectivity information update timer is set to $T_{\text{ciu}}$, it’s related to the number of monitoring nodes $s$ and listening timer $T_{\text{max}}$, then meet the following formula:

$$T_{\text{ciu}} \leq \frac{T_{\text{max}}}{s} \quad (3)$$
After listening timer expires, monitoring nodes finally calculate the number of battlefield radio nodes which is communicating, and count the IP address of each node. The communicating nodes means a node which is sending, receiving or forwarding data packets.

2.1.3. Node adjacency matrix. Monitoring nodes analyze the relationship between originator address, relay address and destination address in each entry of connectivity information recording table, and then build node adjacency matrix \( A(G) = (a_{ij})_{c \times c} \).

All the communicating nodes are simply to a node set \( V = \{v_1, v_2, v_3, \ldots, v_c\} \), \( c \) is the number of communicating nodes. All the communicating links are also simply to an edge set \( E = \{e_1, e_2, e_3, \ldots, e_m\} \) where \( e_k = \{v_i, v_j\} \). Therefore, network topology between all the communicating nodes can be represented as an unweighted undirected graph \( G = (V, E) \), then meet the following formula:

\[
(a_k)_{c \times c} \text{ is node adjacency matrix of the unweighted undirected graph } G, \text{ which is denoted as } A. \text{ The element } a_{ij} \text{ in the matrix } A \text{ indicates whether any two nodes are directly connected from the routing information.}
\]

2.2. Node Importance Evaluation

2.2.1. Shortest routing hops matrix. The element of shortest routing hops matrix records shortest routing hops between any two nodes in adjacency matrix \( A \). The number of 1 hop means that two nodes are directly adjacent to each other. Generally, the algorithms for solving shortest path problem includes Dijkstra algorithm and Floyd algorithm, whose time complexity is \( O(n^2) \) and \( O(n^3) \) respectively, they are not suitable for a large scale Tactical Mobile Ad Hoc Networks. Therefore, this paper optimizes the time complexity of calculating shortest routing hops matrix based on the mathematical nature of power matrix.

We set shortest route matrix as \( H \), and the element of \( H \) meet \( (h_{ij})_{c \times c} = (a_{ij})_{c \times c} \). We set the power matrix \( M \) as the power of \( A \), let \( M = A^\theta \), \( m_{ij}^{(\theta)} \) represents the element in the \( i \)-th row and \( j \)-th column of power matrix \( M \). Considering the nature of adjacency matrix, if \( m_{ij}^{(\theta)} = 1 \), it means that there are \( t \) routing path length equals \( \theta \) between node \( v_i \) and node \( v_j \). Due to the protocol of Tactical Mobile Ad Hoc Networks limits the maximum routing hops to \( \maxHop \), it needs to meet the formula 5:

\[
\theta \leq \maxHop \tag{5}
\]

\( \theta \) iterates from 1 in order. All the elements except the diagonal line and 0 of matrix \( A \) set as \( a_{\mu} \), when there is the first value that makes \( a_{\mu}^{(\theta)} \neq 0 \), the value of \( \theta \) is shortest routing hops between node \( v_k \) and node \( v_\mu \). Now \( \theta \) can be put into matrix \( H \), that meet \( h_{k\mu} = \theta \). If \( a_{\mu}^{(\theta)} = 0 \) when \( \theta = \maxHop \), it indicates that there are unreachable between node \( v_k \) and node \( v_\mu \), and the value of \( h_{k\mu} \) should be set as \( \infty \).

\[
h_{k\mu} = \begin{cases} 
\theta & \text{the first value meet } a_{k\mu} \neq 0. \\
0 & \text{if } b = k. \\
\infty & \text{there are unreachable between } v_k \text{ and } v_\mu. 
\end{cases} \tag{6}
\]

\textbf{Algorithm 1. Calculate Shortest routing hops matrix}

\textbf{Input:} adjacency matrix \( A \)

\textbf{Output:} shortest routing hops matrix \( H \)

1: Initialization: \( H = A \), \( a_\mu \in A \), \( h_\mu \in H \), \( k = 1 \), \( \maxHop = 7 \)
2: // MIL-STD-188-220D protocol limits the maximum routing
3: // hops to 7
4: while \( k \leq \text{maxHop} \) do
5: \( H_i = A^{(k)} \)
6: // calculate the power matrix of \( A \)
7: \( H_z = H_i \times A \)
8: for \( i = 1 \) to \( n \)
9: \( \text{if} \ (H(i,:) = 0 \ & \ H_z(i,:) = 0 \ & \ H_z(i,:) \neq 0) \)
10: \( \text{TMP} = \text{find}(H(i,:) = 0 \ & \ H_z(i,:) = 0 \ & \ H_z(i,:) \neq 0) \)
11: // find a value that meets the condition
12: \( H(i,[\text{TMP}]) = k + 1 \)
13: end if
14: end for
15: \( k = k + 1 \)
16: end while
17: if \( a_v = 0 \) then
18: \( h_v = \infty \)
19: end if

2.2.2. Node Density centrality definition. We define node density centrality mainly consider of two aspects: node degree and the number of routing hops between a node and the node with the specified node degree. Node degree reflects the number of edges associated with the node and all its adjacent nodes. The greater degree of a node, the greater its communication ability with other nodes, the more important it is in the network. Meanwhile, if the average number of routing hops from a node to another node with a higher degree in the whole network is smaller, it means that it is closer to the core of network and has the greater impact on surrounding nodes.

We set the density centrality of node \( i \) as \( \rho_i \), it meets the following formula:

\[
\rho_i = \frac{c \times d_i}{g_i \times \sum_{j=0}^{\infty} h_j + \frac{2}{g_i} \times \sum_{j=0}^{\infty} h_j + \ldots + \frac{k}{g_i} \times \sum_{j=0}^{\infty} h_j}
\]

We use set \( C \) to record all the nodes of a specified degree \( C = \{C_1, C_2, C_3, \ldots, C_k\} \), \( C_i \) records the number of node with degree \( k \), and the number of nodes in \( C_i \) is to set as \( g_i \). Where \( c \) is number of communicating nodes monitored in the whole network, and the value of \( h_j \) can be queried in shortest routing hops matrix. \( d_i \) is the degree of node \( i \), its value is obtained by traversing adjacency matrix \( A \) and adding all the elements \( a_{ij} \) of the \( i \)-th row in matrix \( A \). The value of \( d_i \) meet the following formula:

\[
d_i = a_{i1} + a_{i2} + \ldots + a_{ij}
\]

Node density centrality reflects the closeness between the nodes with higher degrees in the whole network to a certain extent, and it also consider node degree. If a node is further to another node with a higher degree and its degree is small, it indicates that node is seriously deviated from the center of the network and the connectivity is poor than other nodes.

2.2.3. Node importance degree calculation. We finally define node importance degree as a criterion for judging influential nodes of Tactical Mobile Ad Hoc Networks. Tactical Mobile Ad Hoc Networks is a highly real-time network. The traditional methods such as DNC, SLC, and NCC fail to make full use of
features of Tactical Mobile Ad Hoc Networks and ignore the impact of actual traffic flow on influential nodes. The method proposed in this paper takes into account the collection process while calculating node importance degree.

The traffic flow handled by communicating nodes of Tactical Mobile Ad Hoc Networks includes the total traffic that makes data sending, data receiving and data forwarding. The specific process of traffic flow collection is obtained by traversing connectivity information recording table. We set the total traffic flow by node $i$ during the time of listening timer $T_{listen}$ as $f_i$, where the data sent as to $Tx_i$, the data received as to $Rx_i$ and the data forwarded as to $Rl_i$. Node $i$ meets the following formula:

$$f_i = \begin{cases} 
Tx_i + Rx_i & \text{node } i \text{ is a relay node} \\
Tx_i + Rx_i + Rl_i & \text{node } i \text{ is not a relay node}
\end{cases} \tag{9}$$

Normalize node density centrality degree and traffic flow all nodes according to formula 7 and formula 9, and we finally set density centrality of node $i$ as $\tau_i$ and traffic flow of node $i$ as $F_i$, then meet the following formula:

$$\tau_i = \frac{\rho_i}{\sum \rho_i} \tag{10}$$
$$F_i = \frac{f_i}{\sum f_i} \tag{11}$$

Now we define formula 12 for calculating importance degree of node $i$ as follows:

$$r_i = \omega \times \tau_i + \mu \times F_i \tag{12}$$

$r_i$ is density centrality of node $i$. $\omega$ is the impact factor of density centrality of node $i$, it represents the weight value of density centrality assigned by node importance degree. If the value of $\omega$ is larger, the analysis results are more inclined to the distribution, closeness and connectivity between nodes in the whole network when evaluating influential nodes. $\mu$ is the impact factor of traffic flow of node $i$, it represents the weight value of traffic flow assigned by node importance degree. If the value of $\mu$ is larger, the analysis results are more inclined to communicating node’s ability to data information processing. The values of $\omega$ and $\mu$ in this paper meet the condition $\omega + \mu = 1.0$.

3. Experimental Results and Analysis

3.1. NS3 Platform

NS3 is an open source discrete event network simulator which operated in GNU/Linux. A new Python-based complication system is integrated in NS3, which supports more network protocol such as DSR, AODV and OLSR and is easy for user to expand.

In this experiment, NS3 is used to build a model of Tactical Mobile Ad Hoc Networks based on the network between primary battlefield radio nodes and secondary battlefield radio nodes, and monitoring nodes are configured to collect data packets. The specific process of protocol involved in the experiment will not described in this section.

3.2. Experimental Configuration

We initialize five primary battlefield radio nodes to make a primary cluster. Each secondary cluster contains 19 secondary battlefield radio nodes and a primary battlefield radio node, the total number of nodes in the whole network is 100. Figure 3 shows network topology configuration of communicating nodes in this experiment.
Figure 3. Network topology configuration of communicating nodes in the experiment

$S$ represents primary battlefield radio node, $E$ represents secondary battlefield radio node in figure 3. There are 10 traffic flows configured and the packets data rate of each of them is random. We finally put 5 monitoring nodes in the network we configured. Table 1 shows the specific parameter configuration of this experiment.

Table 1. Experimental parameter configuration

| parameter            | value            |
|----------------------|------------------|
| Simulation Time      | 50s              |
| $T_{CT}$             | 2s               |
| Number of Nodes      | 100              |
| $R_{S_{max}}$        | 150m             |
| $R_{E_{max}}$        | 200m             |
| $R_{L_{max}}$        | 250m             |
| Topology Scale       | 2000 m × 2000 m  |
| IP Mask              | 255.255.255.0    |
| Date Transform Type  | Constant Bytes Rate (CBR) |
| Packet Size          | 100 Bytes        |
| Number of Traffic    | 10               |

3.3. Experimental Results

5 Monitoring nodes in the experiment obtained adjacency matrix $A$ through connectivity analysis mechanism in TINE we proposed, which can reconstruct the current topology of the opponent’s network. Figure 4 shows it as follows:
Figure 4. Reconstructing topology of the opponent’s network

In order to verify the effectiveness of TINE method, experimental results will be analyzed from two aspects: topological revivification degree and node importance degree. Topological revivification mainly reflects the coincidence between the reconstructing topology and actual topological configuration, it directly verifies the reliability of TINE method. Node importance degree mainly reflects the results of TINE method. The higher importance degree of the node, the more important the strategic position of this node in the whole network.

All black nodes in figure 4 are primary battlefield radio nodes that are reconstructed. It can be seen from results that all the primary cluster are reconstructed completely. All secondary battlefield radio nodes have data relay in each secondary cluster except originator nodes and destination nodes. Secondary battlefield nodes with IP address of 198.3.5.4, 198.3.5.18 and 198.3.5.19 in cluster No.5 and 198.3.2.11, 198.3.2.17, 198.3.2.18 and 198.3.2.19 in cluster No.2 do not have a direct connection relationship and belong to an isolated subgraph. On the contrary, there are relay relationship between the nodes with IP address of 198.3.3.1, 198.3.3.4 and 198.3.3.16 and other nodes, these nodes are not isolated and are consistent with experimental configuration.

Table 2 shows the comparison experimental results between TINE method and other traditional methods in the case of $\omega = \mu = 0.5$, in which we consider node centrality to be as important as the traffic flow. We only take the top 10 most important nodes in the results. However, DNC, SLC and NCC method are only analyzed from the change of one characteristic parameter in the complex network, TINE method we proposed has made more use of features of Tactical Mobile Ad Hoc Networks.

TINE method is highly consistent with the analysis result of DNC method with better recognition effect. Since DNC method needs to change node adjacency matrix when deleting each node in its algorithm, it is necessary to recalculate or update shortest routing hops matrix when the deleting process is trigging. The time complexity of $n$ nodes will be increased to $O(n^2)$ in DNC method. Compared
with TINE method, we only need to calculate shortest routing hops matrix once and find the value between node pairs with the specified degree. The time complexity of TINE will reduce to \( O(\text{maxHop} \times n) \).

Table 2. In the case of \( \omega = \mu = 0.5 \), the comparison experimental results between TINE method and other traditional methods

| rank | TINE   | DNC    | SLC    | NCC    |
|------|--------|--------|--------|--------|
| 1    | 198.2.1.3 | 198.2.1.3 | 198.2.1.3 | 198.2.1.3 |
| 2    | 198.2.1.4 | 198.2.1.4 | 198.2.1.4 | 198.2.1.2 |
| 3    | 198.2.1.2 | 198.2.1.2 | 198.2.1.2 | 198.2.1.1 |
| 4    | 198.3.3.4 | 198.3.3.4 | 198.3.3.4 | 198.3.2.2 |
| 5    | 198.2.1.1 | 198.2.1.1 | 198.3.3.3 | 198.3.2.5 |
| 6    | 198.2.1.5 | 198.2.1.5 | 198.3.2.2 | 198.2.1.4 |
| 7    | 198.3.2.2 | 198.3.4.2 | 198.3.3.2 | 198.3.3.4 |
| 8    | 198.3.4.2 | 198.3.2.2 | 198.3.3.1 | 198.3.3.3 |
| 9    | 198.3.5.18 | 198.3.4.19 | 198.2.1.1 | 198.3.3.1 |
| 10   | 198.3.1.3 | 198.3.1.3 | 198.3.4.2 | 198.3.3.2 |

4. Conclusion
In this paper, we propose TINE method to recognize and analyze influential nodes in Tactical Mobile Ad Hoc Networks. TINE method is suitable for tactical battlefield radio equipment that use Tactical Mobile Ad Hoc Networks protocol. We use a faster algorithm to calculate shortest routing hops matrix through node adjacency matrix in the mechanism of connectivity analysis. Then we define node density centrality to measure the closeness between the higher degree nodes in the network. Finally, we combine node density centrality with traffic flow, and introduce impact factors to define node importance degree. Experimental results show that our method is better than DNC, SLC and NCC method. The future research work includes the optimization of influential nodes analysis algorithm with a better performance.

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