

Survivability Measure for Multichannel MANET-based Tactical Networks

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Abstract— Several studies for survivability in MANET has been done, but there should be more considerations such as multichannel environment, tactical environment, and link failures. In this paper, we define survivability of tactical networks based on connectivity with multichannel environment and propose a method of measuring survivability of a network. We proposed a survivability measure scheme which calculates the number of links with each hop between nodes and aggregates all the link counts which are calculated in previous steps. When planning networks and performing missions in tactical networks, survivability measure can be contributed to transfer the mission-critical data. It also provides a basis of deciding weak points or connections of networks.

Keywords— survivability; measure; multichannel MANET; tactical network; critical links

I. INTRODUCTION

MANET (Mobile Ad-hoc Networks) has capability of self-configuration between mobile routers (or hosts) with wireless connections so the network may consist of arbitrary topologies. In such a situation, each node should configure and maintain a network, and recover from failure by itself because there is fewer contact point of network for nodes [1]. MANET with these properties have been studied many fields, but there are several problems which are low throughput, noise, link failure, and security issues because the environment of military networks differs from commercial networks in terms of mobility (aircrafts, tanks, or human), obstacles (forest, desert, or buildings), distance between nodes, and unexpected situations (prisoner of war or jamming) in battle field [2].

Military networks should be operated highly dynamically and use wireless links because it is hard to configure the network using wired connection. In addition, increasing demands of data communication and multihop transferring, the device as a router is needed to provide backbone network with high capacity of bandwidth. In this situation, if one of the routers were down, problems such as disruption in the delivery of critical information for missions, or outage state of network may occur. Because of these limitations, network survivability is one of the critical information which should be considered in tactical networks. The goal for operating missions stably and transferring data efficiently in network

management perspective is the maximization of the survivability of network.

Survivability of networks can be defined as various manners [3]-[6]. Different frameworks have been proposed and applied under different scenarios [7]-[9]. Topographical factors such as distance and location is the biggest problem which affects survivability of network compared to other factors in tactical network. Thus, the survivability that secures minimum connectivity of network has great significance. According to this concept, there are many studies for survivability based on connectivity [10]-[12], but these studies did not considered multichannel environment, tactical environment, and link failures. In addition, a proper basis which indicates current situation as numerical manners is needed to react against the failures of tactical network, and survivability measure should be derived.

In case of network using multichannel, nodes can communicate each other with multiple non-overlapping channels. We can troubleshoot the low throughput problem of single channel environment and recover reliability and stability of network because nodes can transfer the data simultaneously without collision or interference.

In this paper, we propose a new survivability measure scheme which is suitable for multichannel tactical MANET. This survivability algorithm provides numerical measurement of topology using connections of network (i.e. links). Also, we propose a scheme to find critical links which are the weakest links of network. This weakest link is attacked frequently due to their weakness. This link requires proper reactions to prevent partition of network or to protect them because the network would be partitioned if the link fails.

The remainder of this paper is organized as follow. Section II presents related works of this paper and Section III proposes survivability measure scheme for multichannel MANET. Section IV presents experiments and comparisons and Section V concludes the paper.

II. RELATED WORKS

Management of connections must be designed to preplan for the expected situations and to react for the unexpected situations. Evaluation of different schemes is important. However, it is not obvious how to evaluate the management schemes, not only because the size and complexity of the

problem is a huge modelling challenge, but also because the definition, metrics, and quantification methods of survivability are not clearly defined. Existing definition of survivability can be summarized as the ability of a system to continuously deliver services in compliance with the given requirements in the presence of failures and other undesired events [13]. The rest of this section is summaries of studies for survivability.

First of all, [10] studied survivability measure based on connectivity. In this study, every node has two state; undamaged and damaged. Network is gradually degraded by destroying one important node of this network. Destroying process continuous until the network is completely disconnected. The important node is the most counted node in counting process of node disjoint independent path so many paths passing through the node will be damaged if the node is down. The survivability is the sum of node connectivity which is summed by JN (Jump Node of independent path). JN is the hop count between two nodes. It is assumed that the network having higher survivability can stand more against the attack. The study showed that topology having higher survivability has higher connection probability to the network. However, there is no consideration of multichannel and link failure in destroying process.

Next, [11] is the study of survivability for information system. There are definition of information system by graph theory and analysis of the system by mathematical methods. They assumed that the survivability of network is zero even if one node is disconnected to the network. They showed the survivability of information system, subsystem, and nodes. However, there was no consideration such as link failure and node down.

Reference [12] is the method of k-connectivity using graph theory. They defined critical node as partitioning the network if the node was down and proposed algorithm finding out multiple critical node of network. They considered node and link criticism and provide a creating method for new proper link, but they did not consider validity of the new link, tactical environment, and multichannel environment.

TABLE 1. NOTATIONS USED IN ALGORITHMS

Notations	Definition
G	Network Graph
V	Nodes in G
E	Direct links in G
e_{ij}	The number of channels between node i and j
n	The number of nodes in G
K	The number of maximum channels
t	Steps in destroying process (the number of critical links removed)
P	Subset matrix of intermediate nodes in paths
p_{ij}^h	Subset of intermediate nodes on path $i-j$ at h hop
p_{xj-i}^h	Subset of intermediate nodes on path $x-j$ at h hop without node i in the subnet
n_{ij}^h	The number of elements of p_{ij}^h
C(t)	Connectivity measure at step t
CL(t)	Critical link at step t from link usage
S(G)	Survivability of network G

TABLE 2. DEFINITIONS FOR IMPORTANT CONCEPTS

Survivability Measure	The measure how the network can continuously provide the link connections against link failures of network at given topology.
Connectivity	The connection degree of connected network that a certain topology has at time t . Connectivity is zero if the topology is disconnected.
Critical link	The weakest and important link of the topology because they have the highest usage of a link.
Partitioning-Critical Link	Subset of critical link that can separate the network if the link is failed.

III. SURVIVABILITY MEASURE FOR MULTICHANNEL-BASED TACTICAL MANET

A. Definition of Survivability Measure for Tactical networks

Survivability measure can be defined in several ways. Many of studies have defined survivability as the ability of a system to continuously deliver services in compliance with the given requirements in the presence of failures and other undesired events [13]. The topology of network has one or more critical links. In this paper, we define survivability measure based on the previous definition and critical link as in the following TABLE 2.

In this paper, we consider an algorithm in multichannel MANET. The nodes in the network are identical and use same numbers of channel. Proposed methods of the survivability measure and of the critical link provide a way to decide stability and reliability of the network. For example, we could find alternative routes having higher survivability measure when a link failure occurs if the survivability measure were used as a routing metric. In addition, the nodes can be deployed in best place which improves the connectivity of a topology. Also, we can use this information as assuring minimum connections of critical point by strengthening the links.

B. An Algorithm of Survivability Measure for Tactical Networks

The survivability of network is measured to know how much the network is survivable. At the situation of destroying process, i.e. one of the critical links of network is down every time, the connectivity of topology of each step is calculated and summed up to survivability. In this section, we model the process of getting survivability measure and critical links. The survivable network can endure more because the network will still be connected even some of the links are down.

ALGORITHM 1. THE SURVIVABILITY PROCESS

INPUT: nodes, 1 hop links between two nodes
 OUTPUT: survivability measure, critical links

Step 1: calculate C(t)
 Step 2: calculate CL(t)
 Step 3: remove one of the critical links in CL(t)
 Step 4: break if network is partitioned, otherwise increase t and repeat Step 1
 Step 5: calculate the S(G) using all C(t)s ; survivability measure of network G

ALGORITHM 2. THE CONNECTIVITY MEASURE ALGORITHM

INPUT: nodes, 1 hop links between two nodes

OUTPUT: connectivity measure, link usage, matrix P

Step 1: make Link matrix E

Step 2: make 2 hops subset of matrix P

Step 3: make 3 or more hops subset of matrix P

Step 4: count the number of elements in cell of matrix P

Step 5: calculate the connectivity of the topology with weighted factor by hops

TABLE 1 describes notations used in our algorithms. ALGORITHM 1 is entire process of survivability. With the iteration, we can get survivability of network by summing all Cs. ALGORITHM 2 shows the steps of the proposed scheme for connectivity of topology.

First of all, we define a domain of the network; nodes will be mapped as graph G; the number of nodes in a given graph G is n :

$$G = \{g_1, g_2, g_3, \dots, g_n\} \quad (1)$$

We can make an edge matrix of graph G as equation (2) in step 1 of ALGORITHM 2:

$$E(t) = \begin{bmatrix} e_{11}(t) & \dots & e_{1n}(t) \\ \vdots & \ddots & \vdots \\ e_{n1}(t) & \dots & e_{nn}(t) \end{bmatrix} \quad (2)$$

where $e_{ij}(t) = \begin{cases} k & k \text{ is the number of channels } (1 \leq k \leq K) \\ 0 & \text{otherwise; (i.e. no connection)} \end{cases}$.

Set matrix P is a matrix that has set of intermediate nodes of path from node i to node j as their elements, i.e. P contains set of sets. Equation (3) is the definition of P.

$$p_{ij}^h(t) = \begin{cases} \emptyset & \text{if } h = 1 \\ \{x\} | e_{ix}(t) > 0, e_{xj}(t) > 0, x \neq i, j\} & \text{if } h = 2 \\ \{e_{ix}(t) * (\{x\} \blacksquare p_{xj}^{h-1}(t)) | x \in V - \{i, j\}, e_{ix}(t) > 0\} & \text{if } h > 2 \end{cases} \quad (3)$$

Step 2 in ALGORITHM 2 is the second case of equation (3). There is an empty set when $h=1$ in the equation (3). In case of $h=2$, the intermediate node x is an element of set $p_{ij}^h(t)$ as an element having only one node. The condition of second case is that there exists one or more links both $i-x$ and $x-j$. The element of set, x , should be an intermediate node of path $i-x-j$. Moreover, the node x should not equal to i or j .

The third case of $p_{ij}^h(t)$ describes step 3 in ALGORITHM 2. It says that h hops link is made of l hop link and $h-l$ hops link. The first part of $h>2$ case means 1 hop link, that is $e_{ix}(t)$, is the number of direct link from node i to intermediate node x . If the hop iterates from $h=3$ to max hops, the entry of $h-1$ hop is already filled at previous iteration. Operator $\blacksquare$ of second part of $h>2$ case is a set operator we defined for this operation. Operation $A \blacksquare B$ is that set A merges to each elements of set B. It is a kind of distribution law of operator. For example, $\{x\} \blacksquare \{\{a\}, \{b\}, \{c, d\}\} = \{\{x, a\}, \{x, b\}, \{x, c, d\}\}$. One of the new notations of $h>2$ case is p_{xj}^{h-1} , which is similar to p_{ij}^h , but there is an exception rule about “-i” subscript of p. Notation p_{xj}^{h-1} is defined as sets of intermediate nodes on path $x-j$, except i as an intermediate node. Thus, the third case of equation (3), that is sets of nodes on $i-j$ with h hops, is sets of

path $i-x-j$ with $i-x$ for l hop and $x-j$ for $h-l$ hops. TABLE 3 shows an example of 2 and 3 hops entries matrix P, but 1 hop entries of matrix E based on Figure 1. .

After all entries of matrix P is filled, we can count the number of sets in the entries of matrix p, which is step 4 of ALGORITHM 2. Let matrix N is the number of sets in each entry, we can make N as following equation (4):

$$n_{ij}^h(t) = \begin{cases} e_{ij}(t) & \text{if } h = 1 \\ |p_{ij}^h(t)| & \text{if } h > 1 \end{cases} \quad (4)$$

where $|p_{ij}^h(t)|$ is the number of elements of $p_{ij}^h(t)$. There are ij as row index and h as column index in matrix N.

Connectivity of given topology is calculated with weight using matrix N. The weighted factor is hop count, which means multihop link has higher probability of failure so the multihop link should have low impact to connectivity. The equation is shown below:

$$C(t) = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \sum_{h=1}^{n-1} \frac{n_{ij}^h(t)}{h} \quad (5)$$

where i and j are node indices shown in (1).

After all of connectivity measure is figured out, i.e. the last connectivity is zero if the network is partitioned, we can sum the connectivity all together as equation (6):

$$S(G) = \sum_{t=0}^{n-1} C(t) \quad (6)$$

where t is steps in destroying process disconnecting one of the critical links. Step t is the number of critical links removed so far.

We should know which link is critical link to transit to next step $t+1$. Critical link is figured out by link usage of matrix P. We, also, count the link usage between node i and j whenever we calculate h hops link from matrix P. For example, there are 3 links on the path $i-j-k-l$ so we increase usage of link $i-j$, $j-k$, and $k-l$. Critical link is determined by maximum counted usage of link. To transit to next step $t+1$, we remove a critical link of topology at step t and repeat the algorithm until the network is partitioned.

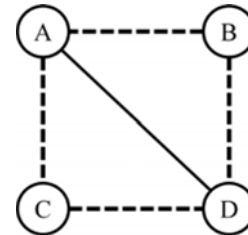


Figure 1. An example of topology

TABLE 3. AN EXAMPLE OF MATRIX P AND MATRIX E

$i-j$	Matrix E	Matrix P	
	e_{ij}	2 hops	3 hops
A-B	1	C,D	-
A-C	1	B	DB
A-D	1	B	CB
B-C	0	A	DA
B-D	1	A	CA
C-D	1	A,B	AB, BA

C. An Example of Connectivity Measure of a Topology with 4 nodes and 4 links

In this section, we explain the algorithm above with example. A network can have various topologies according to their nodes and links. Figure 2. shows an example of network topology. The circles in Figure 2. are nodes of network, and the lines are links of network. This network consists of 4 nodes, those are A, B, C, and D, and there are 4 links connecting two nodes, those are A-B, A-C, B-D, and C-D.

First, we can represent Figure 2. as equation (1), $G = \{\{A, B, C, D\}, \{\{A-B\}, \{A-C\}, \{B-D\}, \{C-D\}\}\}$ and $E(t) = [e_{AB}(t) = 1, e_{AC}(t) = 1, e_{BD}(t) = 1, e_{CD}(t) = 1]$ are made. Multihop link of matrix P can be made using equation (3) with E(t) above. Counting matrix N and the connectivity C_{ij} , and link usage of link $i-j$ are shown in TABLE 4. The survivability of network in Figure 2. is summation of all C_{ij} , and $7.33 (= 1.33 + 1.33 + 1 + 1 + 1.33 + 1.33)$ is calculated.

The critical links of this topology which has maximum usage, are marked as * in TABLE 4. The survivability of network damages largely if these links are down. The critical link assumes the worst case of next step of network. Thus, we can react properly against this weakness to prevent the link failure.

IV. EVALUATION AND COMPARISON

In this section, we validate the algorithm and survivability measure with experiments. First of all, we compare the connectivity of topologies by removing critical link and normal link respectively to validate that one of the critical links is down at each step in destroying process (refer to A). Secondly, we compare the changes of survivability according to the placement of links to the network. It can show the difference between topologies, and we can figure out better topology among various topologies (refer to B). Lastly, we show the relationship between the number of links and survivability (refer to C). A program implementing our algorithm is used in these experiments.

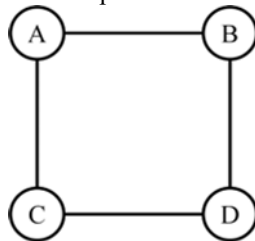


Figure 2. An example of topology with 4 nodes and 4 links

TABLE 4. EXAMPLE OF COUNTING MATRIX N, C_{ij} , AND LINK USAGE

$i-j$	Matrix N (n_{ij}^h)			C_{ij}	Link Usage
	$h=1$	$h=2$	$h=3$		
A-B*	1	0	1	1.33	6
A-C*	1	0	1	1.33	6
A-D	0	2	0	1	0
B-C	0	2	0	1	0
B-D*	1	0	1	1.33	6
C-D*	1	0	1	1.33	6

A. Difference of Connectivity Comparing the Critical Link Failure with Normal Links Failure

In this section, we compare difference of connectivity at critical link failure and normal link failure. Already mentioned in Section III-A, we assume disconnecting critical link every time during destroying process. We should figure out the minimum connectivity of next topology which is one of the links down at next time. That is, the topology having maximum survivability will be the best topology of current situation of network because the sum of minimum connectivity of each topology in destroying process is the guaranteed survivability of the network. Eventually, it can help performing and planning missions with stability and reliably as confirming the minimum value of survivability of network.

Figure 3. shows the example of critical link, and it forms symmetric topology to eliminate partitioning-critical link. It describes (a) base topology of example and (b)-(d) one of links failure. The connectivity of topology is zero if the network is partitioned. For this reason, the cases of partitioning-critical link is excluded to avoid connectivity of next step is zero.

Graph in Figure 4. compares connectivity of topologies in Figure 3. The topology of next step has minimum connectivity if (b) link 1 is down in the result. This result shows the validity of critical link failure.

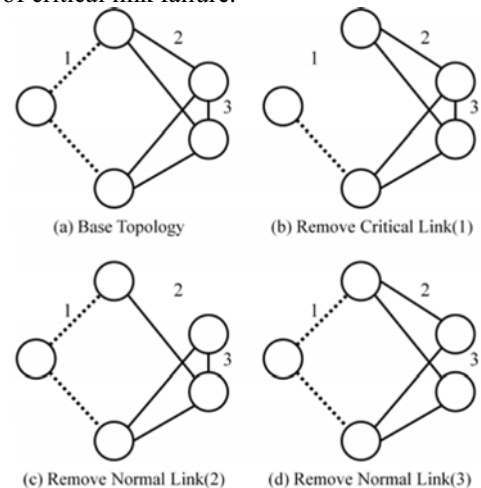


Figure 3. Topologies for comparing their connectivity

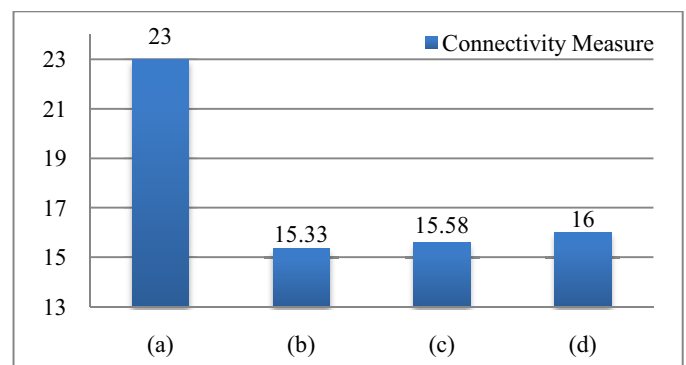


Figure 4. Connectivity of each topology shown in Figure 3.

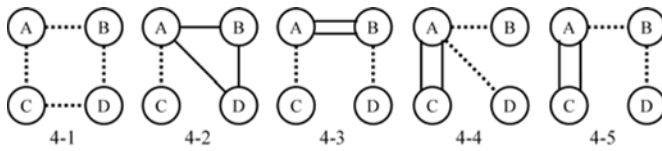


Figure 5. Various examples of topology with 4 nodes and 4 links

TABLE 5. THE COMPARISON OF CONNECTIVITY MEASURE WITH 4 NODES AND 4 LINKS

Link No.	4-1	4-2	4-3	4-4	4-5
Connectivity Measure	7.33	7.16	6.67	6.5	6.16
Critical Link	A-B A-C B-D C-D	A-C	A-C B-D	A-B A-D	A-B B-D

B. Comparing the survivability with 4 nodes and 4 links

The topologies with 4 nodes and 4 links are shown in Figure 5. The dotted lines are critical link of a topology. Let each topologies' name 4-1, 4-2, 4-3, 4-4, and 4-5, and their values of connectivity measure of topology are listed in TABLE 5 which are calculated by the proposed algorithm. In this result, link 4-1 is the best of topologies with survivability 7.33, and also same topology as Figure 2.

C. The Relationship between the Number of Links and Survivability in Destroying Process

With the same manner, Figure 6. represents topologies with best survivability measure for 4 links to 8 links. We can get a comparison of each topology in Figure 6. through destroying process. TABLE 6 which shows the topologies in Figure 6. illustrates the destroying process which removes a critical link of each topology gradually. Survivability and connectivity are increasing when the number of the links in the network increases. At that time, more than one critical links of topology may exist due to the same amount of usage and partitioning-critical links.

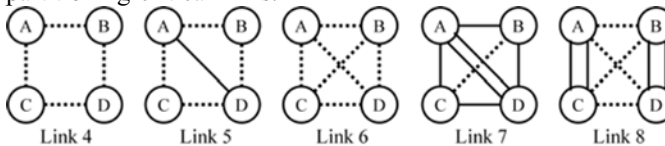


Figure 6. The representative topologies according to the number of links

TABLE 6. THE COMPARISON OF CONNECTIVITY MEASURES AND SURVIVABILITY MEASURE ACCORDING TO DESTROYING PROCESS

Links	Link 4	Link 5	Link 6	Link 7	Link 8
Initial topology	7.33	11	16	21	27.3
Remove 1 Critical Link	4.33	7.16	11	14.67	19.67
Remove 2 Critical Links	0	0	7.16	10	13.16
Remove 3 Critical Links	0	0	0	0	8.33
Remove 4 Critical Links	0	0	0	0	0
Survivability Measure	11.66	18.16	34.16	45.67	68.46

V. CONCLUSIONS

In this paper, we proposed a new survivability measure for multichannel tactical environment. The algorithm we proposed calculates connectivity of each topology in destroying process, which is based on the number of links between nodes. Then, we derived survivability measure by summing these values all together. In addition, we provide critical link that is the weakest and the most used link in the topology. This algorithm can find out survivability of network easily and simply. The topology having higher survivability can endure attacks from enemy or failure in the entire network. Moreover, before performing missions, we can configure a survivable network rapidly and take an action to protect them. It guarantees the transferring of the mission-critical data. In future works, we plan to study a method protecting the critical link and a topology control scheme to configure an optimal topology having better survivability. The node should be mobile, and the reserved nodes can move to weak points.

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