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A network business availability modeling method based on Markov chain

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Abstract

Military tactical networks (MTNs) have grown in size and complexity as the volume of battlefield communications business has increased dramatically. There is a critical need for a quantitative evaluation method to assess the performance of MTNs. Based on the transmission characters of battlefield communication business and the availability of communication equipment, this paper proposed a Markov chain-based network steady-state availability model. Using this model and the analysis of the CSMA/CA transmission protocol as preconditions, a delay-based quantitative evaluation model of network business availability is proposed based on statistical principles. The relationship between network business availability and crucial metrics such as node size and node failure/repair ratio is investigated in simulation experiments to ensure the validity and correctness of the proposed model. The work done in this paper contributes to effectively evaluating the overall availability of MTNs in a complex environment.

Keywords: Markov chain, Steady-state availability, OPNET simulation, Transmission delay, Availability

1 Introduction

Military tactical networks (MTNs) are networks that integrate multi-communications means and multi-business data transmission [1]. MTNs can provide command and control, battlefield situational awareness, and fire coordination for digital combat forces. Its ability to communicate controlling data and situational awareness data has a significant influence on the outcome of a war. The network has gotten a lot of attention since it is going to be a remarkable feature of future wars. Precisely for this reason, the performance analysis of the whole network has been studied widely [3–5].

The following failure factors commonly affect MTNs' availability: network device failure caused by the harsh combat environment; breakdowns caused by different mobility patterns of mobile nodes due to the need to perform different combat tasks; adversary malicious damage to centrality nodes; network topology and routing protocol stability; device or link repairability, and so on. Furthermore, the need for sharing huge volumes of data might influence a network's capacity to execute given activities within set time frames. Such capacity is also one of the key factors that affect the overall availability of MTNs. Moreover, various service demands have varied performance requirements. Some metrics, such as packet loss and transmission delay [6, 7], could objectively reflect the network performance. In some tactical scenarios, the transfer of situational data must be as quickly and efficiently as possible. If the delay threshold is exceeded, the communications network will fail. The availability of MTNs are determined not only by the performance of the communications devices, but also by the transmission requirements of specific business data types.

The traditional availability usually disregards the repairability of network devices. Besides, most existing availability researches mainly consider the network layer, data link layer, or physical layer. Ning et al. [8] proposed an application reliability model in terms of different applications on the same network. The model, which is application-oriented, considers only application-related hardware and services. Yue et al. [9] further studied the influence of the application process on network reliability. They found that congestion of relay nodes would have a greater impact on the reliability of network performance. Moreover, since easing the traffic load of a network [2] and improving the routing strategy are more practical and economical ways to improve network performance, a growing number of publications have focused on them [10–13]. In particular, Li et al. [14] proposed a routing algorithm based on reliable path residual lifetime prediction. Cao et al. [15] proposed a link reliability estimation routing algorithm to ensure that nodes select the best route for reliable communications. The author of [16] proposed a new network performance metric called routing availability, to measure the Quality of Service (QoS) of the network and the quality of video transmission in non-uniform network environments. Besides, Tang et al. [17–19] applied Markov theory to study the quality of service of networks. Zheng et al. [20] proposed an optimization model of business deployment aiming at application reliability.

However, for digital combat forces that rely on MTNs to complete situational awareness sharing and data transmission, more emphasis is placed on the business availability from the perspective of the application layer. Therefore, there are still two important issues that are not considered enough in comparison with the methods and models mentioned above:

(1) The repairability of network devices is not considered or is only considered. The advancement and maintainability of network devices are being enhanced to an unprecedented extent thanks to technological development. However, traditional availability gives little consideration to a network device's reparability. (2) The business availability of a network can better reflect the performance of a network by integrating factors such as the reparability of network nodes, the quality of date link, network topology, routing algorithms, traffic flow, and the network repairability. The end-users, for example, the digital combat forces may pay more attention to the business availability. However, existing models may not consider the networks' performance from the perspective of the application layer.

This paper proposes a novel business availability model based on the Markov steady-state availability model and the CSMA/CA protocol. To evaluate the validity and correctness of the model, we performed simulations using the OPNET simulator.

2 Methods and mathematical model

2.1 Characteristics of MTNs

MTNs are mainly used to enhance combat forces' battlefield situational awareness ability, the cooperation ability of each mobile unit, and the sustainability and timeliness of command and control [21]. As networks that do not rely on pre-existing communication infrastructure, MTNs are the basis of battlefield information sharing and present some distinctive features that deserve to be noted [22]. MTNs are team collaboration of a large number of mobile nodes with self-organization and self-repair abilities. Some key characteristics of these networks are multi-hop, center-less, energy-limited, the need for supporting multi-media real-time traffic, and low delay access to distributed resources [23, 24]. The communication link between any pair of nodes is considered to be dynamic. Due to the burstiness and uncertainty of tactical tasks, mobile nodes arranged in different areas need to quickly move to the designated area within the limited time and organize according to the specific task requirements. The topology of MTNs is flexible and reconfigurable since they can cater for a variety of application scenarios. In addition, MTNs have different requirements for delay, traffic volume, packet loss rate, etc., according to the different specific tasks. For example, in some tactical scenarios, low delay is required for situational awareness data transmission, beyond which the communication network is judged to be a failure; In other scenarios, even if the network is free-flow, the volume of traffic does not meet the requirements, the network is still considered a failure.

2.2 Modeling and analysis for Markov steady-state availability of MTNs

The following definitions and elaborations of reliability and availability are introduced to help better understand the model.

A complex system's reliability can be defined as its capacity to run normally from the beginning of the operation to a certain moment. By contrast, its availability refers to the possibility of normal operation for it may experience multiple failures and repairs during this period. A failure and a repair of a system are regarded as a life cycle. Reliability is the performance evaluation of the system in a life cycle, and availability is in multiple life cycles. To simplify the analysis, we make the following assumptions:

(1) MTN consists of n repairable nodes; (2) The node life X and the node repair time Y obey the exponential distributions with parameters λ and μ, respectively. X and Y are independent of each other; (3) A failed node after repair is considered new, and the node loss is ignored.

The network is operational when k or more nodes are active [27]. When $n\text{-}k+1$ nodes are out of order, the network fails. At this moment, $k\text{-}1$ normal nodes in the network cease working as well, and no failure occurs until one node is repaired. The network will re-enter the running state when k nodes work normally.

The state of the network is defined by the number of failed nodes. $X(t)=j$ means that at moment t, j nodes of the network have failed and are waiting to be repaired.

It can be proved that $\{X(t),\ t\geq 0\}$ is a time-continuous multi-state homogeneous Markov chain [26], and the state transition probability in Δt is as follows:

$$\begin{cases} P_{j,j+1}(\Delta t) = \big(n-j\big)\lambda\Delta t + O(\Delta t), j = 0,1,\ldots,n-k \\ P_{j,j-1}(\Delta t) = j\mu\Delta t + O(\Delta t), j = 1,2,\ldots,n-k+1 \\ P_{jj}(\Delta t) = -\big(n-j\big)\lambda\Delta t - j\mu\Delta t + O(\Delta t), j = 1,2,\ldots,n-k \\ P_{n-k-1,n-k+1}(\Delta t) = -(n-k+1)\mu \\ P_{j,k}(\Delta t) = O(\Delta t),\ \text{others and } j \neq k \end{cases} \tag{1}$$

The state transition probability diagram of the network can be described as (not shown with each state transition to itself):

Then the transition probability matrix $\boldsymbol{A}$ is described as follows:

$$\begin{bmatrix} -n\lambda & n\lambda & & & & & \\ \mu & -(n-1)\lambda-\mu & (n-1)\lambda & & & & \\ & 2\mu & -(n-2)\lambda-2\mu & (n-2)\lambda & & & \\ & & & \cdots\cdots & & & \\ & & & (n-k)\mu & -k\lambda-(n-k)\mu & k\lambda \\ & & & & (n-k+1)\mu & -(n-k+1)\mu \end{bmatrix} \tag{2}$$

$P_j(t)$ represents the probability that the network is in the *j-th* state at moment *t*. The row vector $\mathbf{P}(\mathrm{t}) = \big(P_0(t), P_1(t), \ldots, P_{n-k+1}(t)\big)$ represents the distribution probability of the network in each state at moment *t*. The following relationship can be established as

$$\begin{cases} \mathbf{P}'(t) = \mathbf{P}(t)\mathbf{A} \\ \text{Initial condition } \mathrm{P}(0) \end{cases} \tag{3}$$

The solution is:

$$\mathbf{P}(\mathrm{t}) = \mathbf{P}(0)e^{\boldsymbol{A}t} = \mathbf{P}(0)\sum_{\mathrm{n}=0}^{\infty}\frac{t^n}{n!}\mathbf{A}^{\mathrm{n}} \tag{4}$$

According to the properties of the homogeneous Markov process, we have

$$\lim_{t\to\infty} P_j^{'}(t) = 0, \lim_{t\to\infty} P_j^{'} = \pi_j \tag{5}$$

The following results can be obtained by combining (3):

$$\pi\mathbf{A} = 0, \sum \pi_j = 1 \tag{6}$$

where $\boldsymbol{\pi}$ is that state probability distribution vector in a steady state,$\boldsymbol{\pi} = \big(\pi_0, \pi_1, \ldots, \pi_{n-k+1}\big)$.

Substituting (2) into (6) gives rise to:

$$\begin{cases} -n\lambda\pi_0 + \mu\pi_1 = 0 \\ n\lambda\pi_0 - ((n-1)\lambda + \mu)\pi_1 + 2\mu\pi_2 = 0 \\ (n-1)\lambda\pi_1 - ((n-2)\lambda + 2\mu)\pi_2 + 3\mu\pi_3 = 0 \\ \cdots\cdots \\ \big(n-j\big)\lambda\pi_j - \big(\big(n-\big(j+1\big)\big)\lambda + \big(j+1\big)\mu\big)\pi_{j+1} + \big(j+2\big)\mu\pi_{j+2} = 0 \\ \cdots\cdots \\ k\lambda\pi_{n-k} - (n-k+1)\mu\pi_{n-k+1} = 0 \\ \sum \pi_j = 1 \end{cases} \tag{7}$$

then π_j can be obtained by solving this linear system of equations, and the steady-state availability could be described as:

$$A = \sum \pi_i, i = 0, 1, 2, \ldots, n - k \tag{8}$$

where A means the sum of probabilities when various network devices are in a steady state of normal operation. When the running time of the network tends to be infinite, its availability state will tend to be steady to some extent.

2.3 Business availability based on CSMA/CA protocol

As a prevailing random-access algorithm for wireless LANs, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used to get avoided of data transmission conflicts among nodes as much as possible. It is frequently used in MTNs. CSMA/CA employs the Binary Exponential Backoff Algorithm. A node must wait for a certain time interval when it wants to send a data frame. Besides, a random backoff time is calculated so that data transmission conflicts can be avoided when trying to access the channel again. In this paper, delay performance is taken as an example to model and analyze the business availability of the network.

It is common for multiple nodes to compete for the channel in wireless networks. The analysis in this paper is based on the following assumptions:

(1) n nodes are competing for the channel to transmit data;
(2) There is no hidden node and the channel is ideal;
(3) The transmission queue for each node is always non-empty.

The Markov model is established according to the characteristics of individual nodes in the network. This model can deduce the probability p of a node to have a conflict in a data transmission within a random time interval. Moreover, it can also derive the steady-state probability (τ) of a node transmitting a data frame in a random time interval. In the Binary Exponential Backoff Algorithm used in CSMA/CA, the backoff time is chosen uniformly in the range *(0, w—1)*, where w represents the size of contention window whose size depends on the number of retransmissions of the data frame. W_0 is the minimum size of backoff window. $W_m = 2^m W_0$, where m is equal to the number of retransmissions, $m \in [0, M]$, and M is the maximum backoff order.

s(t) is the stochastic process of the node's backoff order, while *b(t)* is the stochastic process of the node's backoff time counter at moment t. Each data frame attempts to be sent without regards to its retransmission count. The data frames conflict at a constant and independent probability p. The discrete-time Markov chains of the two-dimensional stochastic process *{s(t), b(t)}* are modeled as:

the non-empty one-step transition probability is:

$$\begin{cases} P\{i,k|i,k+1\} = 1, k \in (0, W_i - 2), i \in (0, m) \\ P\{0,k|i,0\} = (1-p)/W_0, k \in (0, W_i - 1), i \in (0, m) \\ P\{i,k|i-1,0\} = p/W_i, k \in (0, W_i - 1), i \in (1, m) \\ P\{M,k|M,0\} = p/W_M, k \in (0, W_M - 2) \end{cases} \tag{9}$$

The above equation explains the following in order:

(1) At the beginning of each time interval, the backoff time decreases;

(2) After a data frame is successfully transmitted, the backoff order of a new data frame starts from 0;
(3) The backoff order increases if a data frame fails to transmit at a backoff order of *i-1*;
(4) The backoff order will not increase when the backoff order reaches the maximum *M*.

All nodes transmit data frames only when the backoff counter is 0. Then p and τ could be calculated as follows

$$p = 1 - (1 - \tau)^{n-1} \tag{10}$$

$$\tau = \frac{2}{1 + W_0 + pW_0 \sum_{i=0}^{m-1} (2p)^i} \tag{11}$$

where $(1 - \tau)^{n-1}$ is the probability that none of the other $n - 1$ nodes transmits a data frame.

Then the probability P_S that a data frame is successfully transmitted; the probability P_N that a data frame is not transmitted; and the probability P_C that a data frame is transmitted but conflicts occur could be described as follows:

$$P_S = n\tau(1 - \tau)^{n-1} \tag{12}$$

$$P_N = (1 - \tau)^n \tag{13}$$

$$P_C = 1 - P_S - P_N \tag{14}$$

The average size of the backoff window is an important part of delay analysis. In the backoff stage j, the size of backoff window obeys a uniform distribution in the range $\left[0, W_j - 1\right]$. This indicates that in addition to the selection of the minimum and maximum size of backoff window, the size of the average backoff window W is also related to the conflict probability p. That is, the average size of backoff window is related to both the size of the backoff window for the successful transmission phase and the size of the window that has been backed off before the successful transmission phase.

The average size of backoff window for each round could be calculated as:

$$W_{\text{ave}} = \sum_{i=0}^{M} \frac{W_i - 1}{2} p^i \frac{W_i + 1}{2} (1 - p)\tau \tag{15}$$

The following equations can be used to calculate the average busy time (T_s) of the channel when the transmission is successful and the average busy time (T_c) of the channel when the transmission is in conflict:

$$T_s = D_{\text{IFS}} + H + E_D + \delta + S_{\text{IFS}} + A_{\text{CK}} \tag{16}$$

$$T_C = D_{\text{IFS}} + H + E_D + \delta \tag{17}$$

where H is the total length of the physical and MAC layer header fields; D_{IFS} is the distributed inter-frame spacing; S_{IFS} is the short inter-frame space; δ is the transmission delay; and E_{D} is the average data frame transmission delay.

The average transmission delay (E_{D}) could be calculated as:

$$E_{\mathrm{D}} = (E_{\mathrm{B}} + T_{\mathrm{S}}) + E_{\mathrm{C}}(E_{\mathrm{B}} + T_{\mathrm{C}} + T_0) \tag{18}$$

where E_{B} is the average backoff time of data frames; E_{C} is the average number of conflicts that occur for successful transmission of data frames.

The delay probability distribution $f_D(t)$ is obtained from the average data frame transmission delay (E_{D}) and the corresponding probability of occurrence.

Then, the compliance rate of specific indicators P_{D} can be obtained based on the indicator threshold D_{B} required by the battlefield mission, i. e., the probability that the delay value does not exceed the threshold:

$$P_{\mathrm{D}} = \int_0^{D_{\mathrm{B}}} f_{\mathrm{D}}(t)\mathrm{d}t \tag{19}$$

According to the definition of the compliance rate, P_{D} can also be expressed as the ratio of the number of data frames $\left(Q_{(E_{\mathrm{D}} \leq D_{\mathrm{B}})}\right)$ whose average data frame transmission delay (E_{D}) is less than or equal to the threshold (D_{B}) to the total number of data frames Q_{all}:

$$P_D = \frac{Q_{(E_D \leq D_B)}}{Q_{all}} \tag{20}$$

There is a possibility that the network is in an unavailable state, but the performance meets the criteria when the number of failed nodes in the network does not exceed a certain value. Therefore, we propose a business availability model that is defined as

$$A_{\mathrm{p}} = P_{\mathrm{D}} * A. \tag{21}$$

That is, the steady-state availability is multiplied by the compliance rate of the metrics to evaluate the business availability of the network.

3 Simulation results and discussions

To verify the validity and accuracy of the above theoretical model, simulation experiments were designed. The experimental results will be compared with their theoretical conterparts in this section. First of all, in order to accurately simulate the nodes' failure and repair behavior so that the actual situation of network operation could be more effectively stimulated, this paper establishes the node fault model using the OPNET simulator. Secondly, according to the failure and repair events generated by the node fault model, the proposed Markov steady-state availability model was verified. Moreover, the business availability model could be verified. Finally, through the simulation experiments of different node sizes, the correctness and practicability of the business availability model based on transmission delay applied in the MTNs were verified.

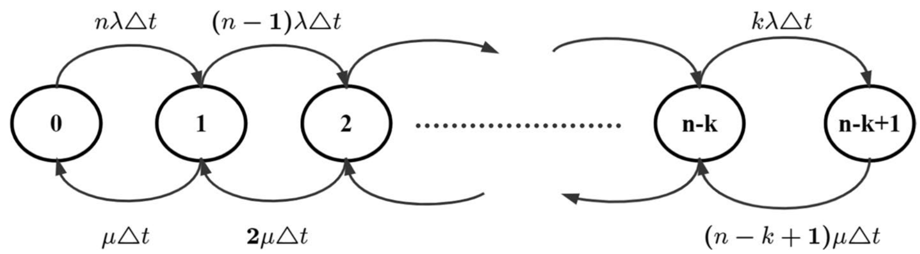


Fig. 1 Network state transition probability diagram. This figure describes the state transition probability diagram of the network. The state $X(t)$ of the network is defined by the number of failed nodes. $X(t)=j$ ($j=0$, 1, 2, … $n-k+1$) means that at moment t, j nodes of the network have failed and are waiting to be repaired. The λ and μ are the parameters of exponential distributions that the node life and the node repair time obey, respectively

3.1 Node fault model based on OPNET

OPNET is an excellent tool for simulating real-life networks, evaluating their performance, and identifying latent problems before they arise [25]. To accurately simulate the behavior of nodes and further effectively achieve the purpose of validating the theoretical model in this paper, firstly, the Fail/Recover node model, namely node fault model, was established based on the OPNET simulator so that it can simulate the failure and repair of nodes according to the probability distribution requirements. When the node is in the Fail state, it stops receiving and sending data. When the node is in the Recover state, it receives and sends data normally. The node states alternate between Fail and Recover. The successive Fail and Recover states are independent. As what was mentioned before, the node Fail and Recover state durations obey an exponential distribution.

3.2 Simulation on the Markov steady-state model

MTNs' availability state changes due to the occurrence of failure and repair events and the changes in network state are discrete in time. This indicates that the entire network is a discrete system and discrete events can be used to drive the simulation process forward (Figs. 1, 2).

The network's topology during simulation verification could be customized according to needs. In this section, a simulation scenario consisting of 10, 20, and 30 nodes is applied as an example to verify the steady-state availability model. The network topology is shown in Fig. 3. Events that drive the simulation process are divided into failure and repair events. After repair, the failure node will recover and be consistent with a new node. The wear and tear of a node will be ignored. If the number of normal working nodes (K) in the network is less than 6, 12, and 18, the network is determined to be unavailable. The mathematical description of the current state of the network could be described as:

$$\Phi(x) = \begin{cases} 0, \ P < K \text{ when in state } x \\ 1, \ P \geq K \text{ when in state } x \end{cases} \tag{22}$$

where $\Phi(x)$ denotes the state value, and a state value of 0 means the network is unavailable; a state value of 1 means the network operates normally. P is the number of working nodes when the network is in state x.

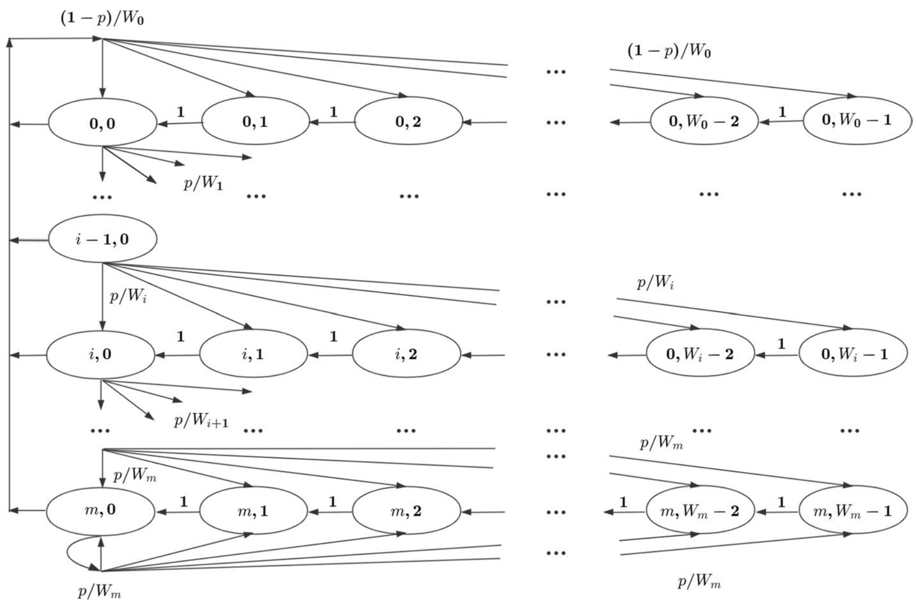


Fig. 2 Markov chains of the two-dimensional stochastic process. This figure describes the discrete-time Markov chains of the two-dimensional stochastic process {*s*(*t*), *b*(*t*)}. *s*(*t*) is the stochastic process of the node's backoff order, while *b*(*t*) is the stochastic process of the node's backoff time counter at moment *t*. The data frames conflict at a constant and independent probability *p*. W_i ($i = 0, 1, 2, \ldots m$) is the size of backoff window, where *m* is equal to the number of retransmissions, $m \in [0, M]$, and *M* is the maximum backoff order

The data packet size is 1024 bytes. The failure/repair ratio is the ratio of the average time between failures to the time it takes to repair. The four failure/repair ratios T_1, T_2, T_3, and T_4 are set for simulation to obtain the network steady-state availability and related node failure probability. The parameter configurations are shown in Table 1.

We build the node fault model using MTNs features as well as modeling assumptions and analyses, and we get the steady-state availability of the network via extensive simulation experiments, as shown in Tables 2, 3, and 4. With the same parameter settings, we derive the theoretical results based on the Markov steady-state model presented in Sect. 2.2, as shown in Table 5, Table 6, and Table 7. When the experimental results with various numbers of nodes are compared, it can be seen that the higher the number of nodes, the lower the steady-state availability of the network with the same failure/repair ratio.

(Steady-state availability, T_i) denotes the steady-state availability, when the network reaches steady-state in a tactical scenario with a failure/repair ratio of T_i. It can be observed that the failure/repair ratio decreases, i.e., the nodes are faulty more of the time, and the availability of the network is significantly decreased. In the table, (P_i, T_i) denotes the probability of *i* failure nodes in the network where the failure/repair ratio is T_i. It can be observed that $\left(\text{Steady} - \text{state availability}, T_i\right) = \sum (P_i, T_i)$. The experimental results based on the node failure model are very close to the results of the Markov model in this paper, as shown in Fig. 4, confirming the validity of the Markov steady-state availability model in this paper, i.e., Eq. 8.

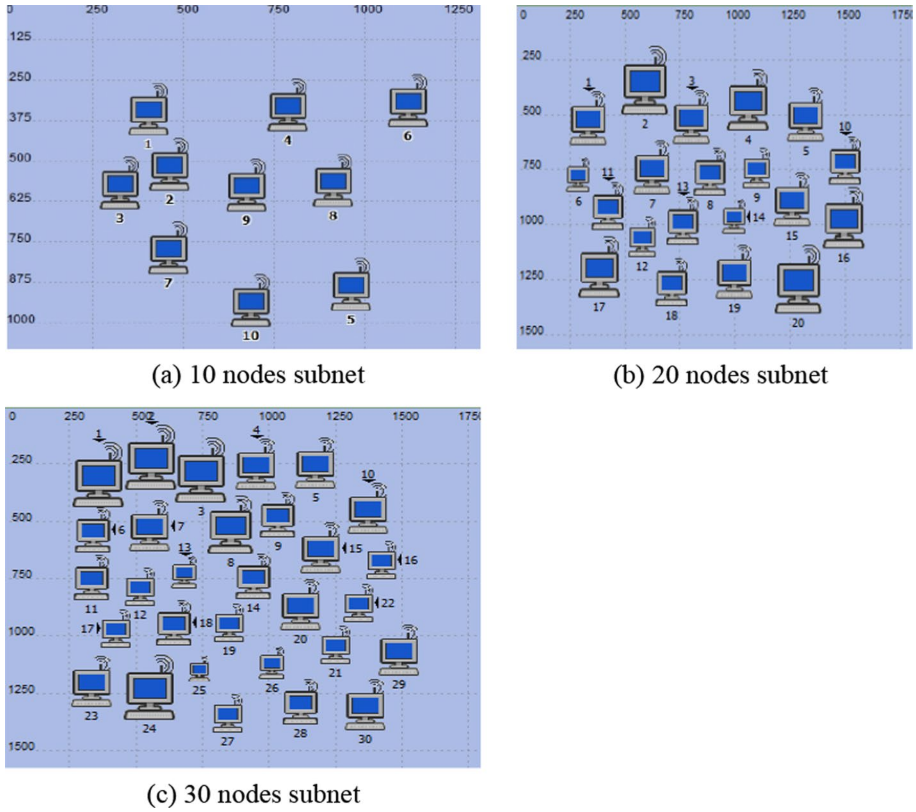


Fig. 3 Network topology. A simulation scenario consisting of 10, 20, 30 nodes is applied as an example to verify the steady-state availability model

Table 1 Simulation parameters

Time between failures (minute)	T_1	T_2	T_3	T_4	Simulation duration (minute)
2000	100/1	20/1	10/1	5/1	8000

Table 2 10 nodes simulation results based on Node Fault Model

Method	**K/N**	**Parameter**	T_1	T_2	T_3	T_4
		Steady-state availability	**98.20%**	**96.60%**	**95.80%**	**94.60%**
Node fault model	6/10	P_0	0.9840	0.4500	0.3200	0.3120
		P_1	0.0120	0.2740	0.2600	0.3060
		P_2	0.0040	0.1700	0.1860	0.1600
		P_3	0	0.0520	0.1600	0.1340
		P_4	0	0.0140	0.0220	0.0240
		P_5	0	0.0060	0.0100	0.0100

3.3 Simulation on the business availability model

We verified the Markov steady-state availability model for MTNs, which is used to quantify the general ability of MTNs to work properly. However, whether the transfer of huge amounts of business data between nodes satisfies the needs of tactical tasks

Table 3 20 nodes simulation results based on Node Fault Model

Method	**K/N**	**Parameter**	T_1	T_2	T_3	T_4
		Steady-state availability	**98.73%**	**75.35%**	**73.89%**	**52.43%**
Node fault model	12/20	P_0	0.8964	0.3341	0.2189	0.2124
		P_1	0.0805	0.1934	0.1801	0.1205
		P_2	0.0104	0.1320	0.1760	0.1070
		P_3	0	0.0846	0.1007	0.0604
		P_4	0	0.0094	0.0602	0.0230
		P_5	0	0	0.0030	0.0010

Table 4 30 nodes simulation results based on Node Fault Model

Method	**K/N**	**Parameter**	T_1	T_2	T_3	T_4
		Steady-state availability	**99.20%**	**92.03%**	**84.81%**	**54.62%**
Node fault model	18/30	P_0	0.7160	0.4841	0.2924	0.2062
		P_1	0.2003	0.1940	0.2308	0.1503
		P_2	0.0651	0.1289	0.1531	0.1030
		P_3	0.0106	0.0928	0.1062	0.0659
		P_4	0	0.0145	0.0626	0.0160
		P_5	0	0.0060	0.0030	0.0048

Table 5 10 nodes theoretical results based on Markov

Method	**K/N**	**Parameter**	T_1	T_2	T_3	T_4
		Steady-state availability	**100%**	**98.97%**	**97.91%**	**95.43%**
Markov	6/10	P_0	0.9446	0.5381	0.3803	0.3110
		P_1	0.0533	0.2640	0.2506	0.2408
		P_2	0.0021	0.1214	0.2008	0.1915
		P_3	0	0.0544	0.0863	0.1550
		P_4	0	0.0087	0.0439	0.0430
		P_5	0	0.0031	0.0172	0.0130

Table 6 20 nodes theoretical results based on Markov

Method	**K/N**	**Parameter**	T_1	T_2	T_3	T_4
		Steady-state availability	**99.95%**	**78.05%**	**76.36%**	**50.29%**
Markov	12/20	P_0	0.8112	0.3470	0.3132	0.1986
		P_1	0.1698	0.2022	0.2358	0.1290
		P_2	0.0175	0.1693	0.1052	0.0782
		P_3	0.0010	0.0497	0.0667	0. 0516
		P_4	0	0.0109	0.0267	0.0420
		P_5	0	0.0014	0.0160	0.0035

is also one of the key facets influencing MTNs' availability. Because of the characters of MTNs, we quantify the compliance rate of delay and the Markov steady-state availability of the network, respectively, to validate the business availability model

Table 7 30 nodes theoretical results based on Markov

Method	K/N	Parameter	T_1	T_2	T_3	T_4
		steady-state availability	**98.03%**	**89.95%**	**80.20%**	**57.84%**
Markov	18/30	P_0	0.7415	0.3511	0.3529	0.2296
		P_1	0.2224	0.2490	0.1832	0.1523
		P_2	0.0127	0.2037	0.1505	0.1002
		P_3	0.0036	0.0702	0.1022	0.0634
		P_4	0.0001	0.0176	0.0098	0.0251
		P_5	0	0.0079	0.0034	0.0078

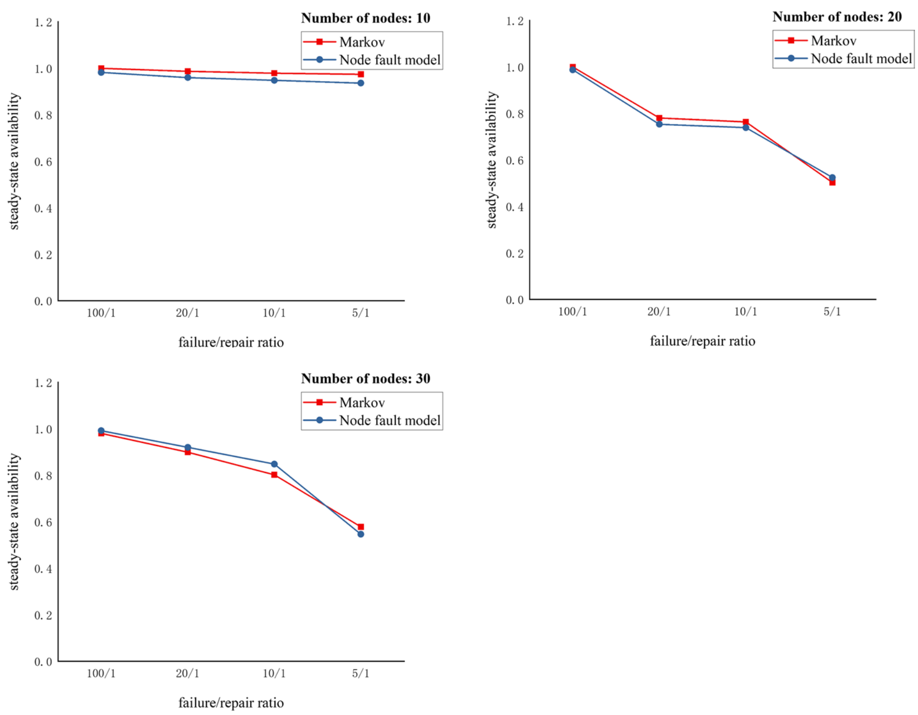


Fig. 4 Comparison of theoretical and simulated values of steady-state availability

presented in this paper, i.e., Eq. 21. Set the parameters provided in Table 8. The network topology is shown in Fig. 5.

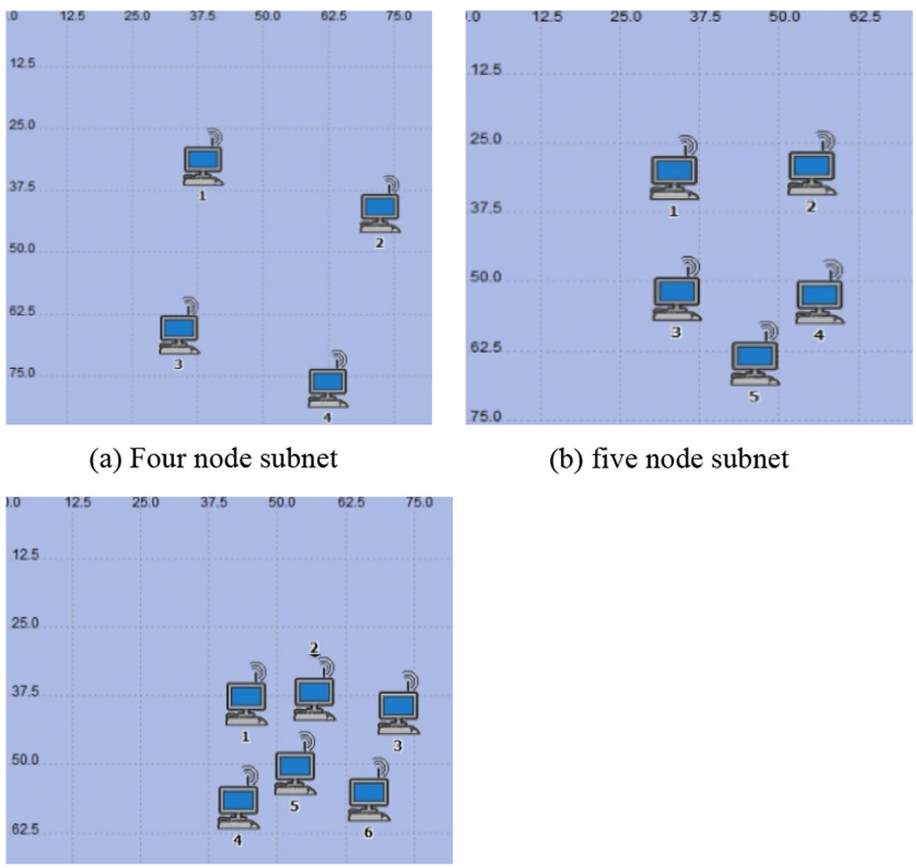
Based on the same parameter and statistical principles, we theoretically estimated the probability distribution of the delay compliance rate for different numbers of node, respectively. The results are shown in Fig. 6, where the abscissa represents the delay value, and the ordinate represents the proportion of packets corresponding to the delay value to total packets. And the yellow straight line represents the delay threshold.

Simulation experiments were performed under the same parameters, and the results are shown in Fig. 6, where the blue, red and green curves represent the simulation results when the number of nodes is 4, 5, and 6, respectively.

In the three simulation scenarios, the number of successfully transmitted data packets and their transmission delay is counted. The results are shown in Fig. 7, where the

Table 8 Simulation parameters

Parameter	Value
Time interval (μs)	50
Distributed Inter-frame Spacing (μs)	128
Short inter-frame space (μs)	28
Minimum competition window	16
Maximum competition window	1024
Acknowledge character (bit)	112
Time delay threshold (ms)	400
Packet size (byte)	1024
Simulation time (min)	30
Number of nodes	4, 5, 6
Simulation scene size (m)	100*100



(a) Four node subnet (b) five node subnet

(c) Six node subnet

Fig. 5 Three simulation scenarios with different numbers of nodes. Three simulation scenarios with different numbers of nodes verify the delay-based business availability model in MTNs

horizontal and vertical axes represent the delay value and the data packet amount corresponding delay (Fig. 8).

The theoretically calculated delay compliance rate and the statistical delay compliance rate based on experimental results both follow the same trend, with both delay

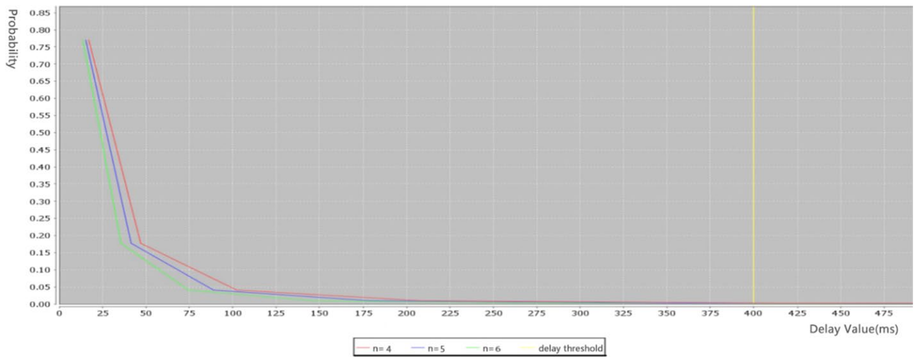


Fig. 6 Theoretically calculated delay compliance rate. The abscissa represents the delay value, and the ordinate represents the proportion of packets corresponding to the delay value to total packets. And the yellow straight line represents the delay threshold. The blue, red, and green curves represent the results when the number of nodes is 4, 5, and 6, respectively

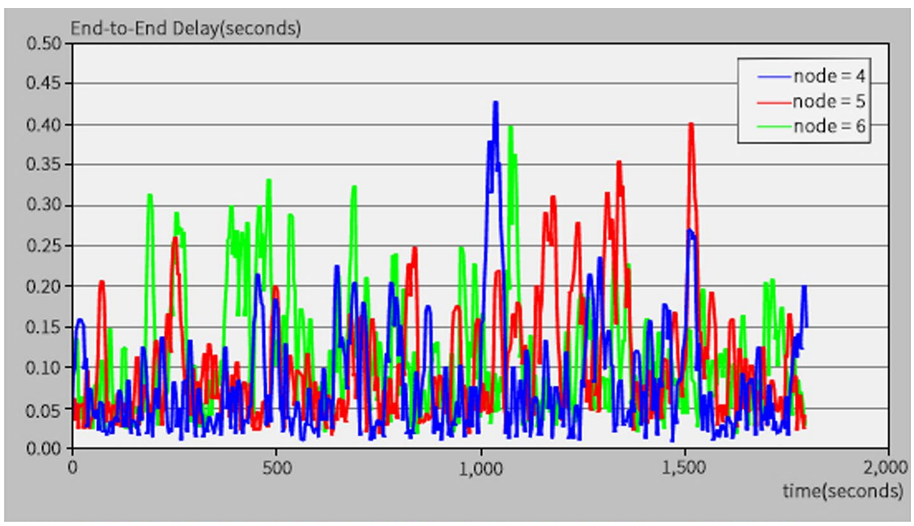
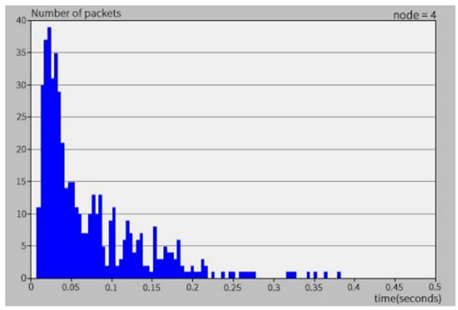


Fig. 7 Delay based on OPNET in three simulation scenarios. This figure shows the simulation result. The blue, red, and green curves represent the simulation results when the number of nodes is 4, 5, and 6, respectively

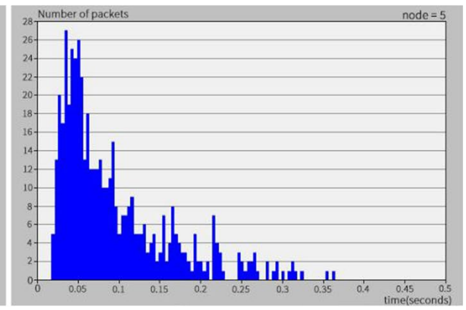
values primarily distributed between 0 ms and 0.1 ms. The results for both are shown in Table 9.

In the results shown in Table 9, the theoretically calculated delay compliance rate is overall higher than the results of the simulation experiments. The deviation between the two gradually increases with the number of nodes. However, it never exceeds 10%, and the mean deviation is 1.75%.

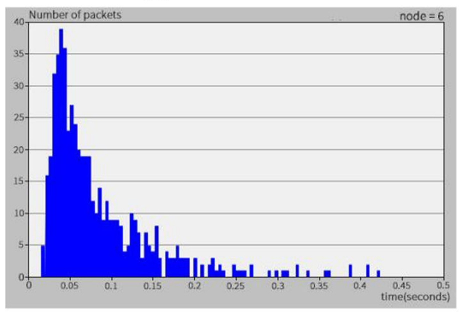
Once the current network's Markov steady-state availability and delay-based compliance rate are determined, the delay based business availability can be calculated using Eq. 21, and the results are shown in Table 10. Under the same delay threshold, it can be seen that the network's business availability declines as the number of nodes grows. The difference between the theoretical and experimental results is within an acceptable range, indicating that the network business availability suggested in this paper is useful for evaluating the availability of complex MTNs and giving some contributions to the research of MTNs availability evaluation methods.



(a) Four node subnet



(b) Five node subnet



(c) Six node subnet

Fig. 8 Delay distribution based on OPNET in three simulation scenarios. This figure shows the number of data packets and their transmission delay, in the three simulation scenarios

Table 9 Delay compliance rate and the deviations

Size of network	Delay compliance rate		Deviation (%)	Mean deviation (%)
4-node network	Theoretical calculation	0.9993	1.03	1.75
	Experimental result	0.9890		
5-node network	Theoretical calculation	0.9985	1.25	
	Experimental result	0.9860		
6-node network	Theoretical calculation	0.9916	2.96	
	Experimental result	0.9620		

Table 10 delay-based business availability of model and simulated experiments

Size of network	Delay compliance rate		Steady-state availability	Delay-based business availability
4-node network	Theoretical calculation	0.9993	0.9998	0.99910014
	Experimental result	0.9890	0.9964	0.98543960
5-node network	Theoretical calculation	0.9985	0.9896	0.98811560
	Experimental result	0.9860	0.9751	0.96144860
6-node network	Theoretical calculation	0.9916	0.9957	0.98733612
	Experimental result	0.9620	0.9842	0.94680040

4 Conclusion

The military tactical network is a complex system, and its availability is affected by many factors. In order to evaluate the network performance as accurately as possible, a reasonable method must be proposed. On the basis of Markov steady-state availability modeling and considering the delay performance of the network, this paper constructed a business-based availability evaluation method for the MTNs, and made a quantitative evaluation on the availability of the network's delay performance. The study has certain significance for the evaluation of the effectiveness, stability and availability of military complex network business.

Abbreviations

MTNs	Military tactical networks
CSMA/CA	Carrier-sense multiple access with collision avoidance

Author contributions

Y.L, Y.C and Y.F have contributed the theoretical and modeling part of this paper, result analysis and completed the writing of the paper. J.L, N.F, Q.G designed and completed the experiment. All authors read and approved the final manuscript.

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Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests

The authors declare that they have no competing interests.

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