

PRAKTYCZNE PODEJŚCIE DO OCENY NIEZAWODNOŚCI APLIKACJI SIECIOWYCH

A PRACTICAL APPROACH FOR NETWORK APPLICATION RELIABILITY ASSESSMENT

Wiele różnych aplikacji może być obsługiwanych przez tę samą sieć. Wymagania użytkowników i kryteria uszkodzeń mogą być odmienne dla różnych aplikacji. Ocena sieci winna być przeprowadzana z punktu widzenia aplikacji. W niniejszym artykule, zaproponowano metodologię oceny niezawodności aplikacji sieciowych opartą na indeksach warstwowych (layered indices). Pierwszym krokiem w omawianej metodzie jest osobne obliczenie niezawodności poszczególnych aplikacji w sieci. Następnie ocenia się niezawodność sieci biorąc pod uwagę związki pomiędzy różnymi aplikacjami. Jako swój wkład niniejszy artykuł (1) przedstawia naukową i praktyczną metodę oceny niezawodności aplikacji sieciowych; (2) tworzy hierarchiczną strukturę do oceny niezawodności aplikacji sieciowych; (3) proponuje i analizuje cztery kluczowe technologie—doboru komponentów, upraszczania sieci, modelowania profilu aplikacji oraz oceny niezawodności aplikacji; (4) ilustruje proponowany proces oceny na przykładzie sieci komputerowej.

Słowa kluczowe: sieci, niezawodność, ocena, aplikacje.

Many different applications may be handled by the same network. For different applications, the user requirements and failure criterions may be different. The network reliability assessment needs to be conducted from the “application” point of view. In this paper, a methodology for network application reliability assessment based on layered indices is proposed. Firstly, the individual application reliability is calculated for each application on the network. Then the network reliability is evaluated considering the relationships among different applications. The contributions of this paper are: (1) a scientific and practical network application reliability assessment method is proposed based on network applications; (2) a hierarchical structure for network application reliability assessment is constructed; (3) four key technologies, component selection, network simplification, application profile modeling, and application reliability assessment, are proposed and analyzed; (4) a computer network is used to illustrate the proposed assessment process.

Keywords: networks, reliability, assessment, applications.

Acronmy

BER	bit error rate
FTP	file transfer protocol
PC	personal computer
PLR	packet loss rate

Notation and Definitions

P_i	probability of selecting component i
P	fraction of components to be selected
\bar{T}_i	average traffic handled by component i
I_i	importance of component i
C_i	buffer capacity of component i
B_i	bandwidth of component i
T_i	traffic of component i
r_c	similarity coefficient of buffer capacity
r_b	similarity coefficient of bandwidth
r_t	similarity coefficient of traffic
n	number of the measured components
m	number of the measured parameters
TMT	total measuring time

δT	measuring time interval
$FC(j)$	failure criterion for parameter j
$Num(i, t)$	number of transmissions on component i by time t
$PFNum(j)$	number of failures for parameter j
$PV(j)$	parameter value for parameter j
$CRI(i, t)$	reliability index for component i by time t
$IARI(t)$	reliability index for an individual application by time t
$AppGroup$	sequence number of the application group
$Sequence$	sequence number of the application in a group
$Leaf(i, j)$	son group sequence number of application j in group i
$MotherGroup$	sequence number of the mother group
$MotherSeq$	sequence number of the mother application in the mother group
$AppNum(i)$	number of applications in group i
$ARI(i, j, t)$	reliability index for application j in group i by time t
$RI(t)$	network application reliability index by time t

$RI_{ij}(t)$	reliability index of component j for application i by time t
$CLRN_{ij}(t)$	number of packets of component j that the parameter <i>connection loss rate</i> exceeds its threshold for application i by time t
$DN_{ij}(t)$	number of packets of component j that the parameter <i>delay time</i> exceeds its threshold for application i by time t
$PLRN_{ij}(t)$	number of packets of component j that the parameter <i>packet loss rate</i> exceeds its threshold for application i by time t
$BERN_{ij}(t)$	number of packets of component j that the parameter <i>bit error rate</i> exceeds its threshold for application i by time t
$N_{ij}(t)$	number of packets of application i that flow through component j by time t
$RI_i(t)$	reliability index for application i by time t

1. Introduction

Networks are used in both civil and military applications. Network reliability analysis and assessment has posed various challenges for both researchers and practitioners. Network reliability assessment methods can be divided into three categories, namely, analytical, simulation, and testing methods. In the 1950's, Lee [3] and Moore & Shannon [21] studied network connection reliability for the first time. In the past 50 years, many researchers have developed advanced network reliability assessment algorithms [1, 4, 6, 7, 24, 25]. Most of these reported algorithms are based on the topology only, while measures from the "application" point of view are neglected. Since the 1980s, as networks become larger in scale and network load increases rapidly, network congestion and traffic delay have become key issues attracting major attention in network reliability research. Barberis and Park [16] investigated network performance considering both delay and throughput. Their research marked a new era of network reliability analysis as they examined networks from the "service" point of view. However, their study was still centering on network topology as they did not distinguish the difference among various applications.

Though some network simulation software packages for computer networks, communication networks, power distribution networks, and transportation networks have appeared in the market [11, 15], they usually focus on the network performance assessment only and neglect network reliability. There is a need for new methodology which can guide network reliability design, analysis and assessment from a global point of view. Existing network reliability assessment systems have the following pitfalls:

- Network failures are not well defined;
- It is difficult to evaluate large scale networks;
- Topology is focused while the application point of view is ignored;
- Network reliability indices are seldom expressed as a function of time. That is, the network reliability is often expressed as a fixed value, while the network dynamic characteristics are not addressed.

2. Conceptual Analysis

Let's first visit the definition of network. *Network* is the basic facility composed of several components connected together, and is used to perform certain applications. A *component* may be a software module or a physical device. *Application* refers to a group of activities which may be related to one another. The *connection* among components may be physical or non-physical and is dependent on the specific application.

According to the definition of system reliability [8, 9, 10], *network reliability* is defined as the capability that the network will accomplish its designated mission in a satisfactory manner for a given period of time when used under specified operating conditions. *The specified operating conditions* include the network use mode (namely, applications running on the network), as well as its external environment (including the natural environment and the literature environment). *The given period* means the time interval for the assessment. *The designated mission* includes network functions and technical indicators. The network function can be summarized as transmitting material, energy or information timely, completely and correctly. Its technical indicators are the performance indicators such as delay, loss rate, error rate, etc.

Using the definitions given above, if the applications are not distinguished, it is hard to define *the designated mission*. Take an aviation enterprise network as an example. The function of a security software module is to disconnect the link if the client has not accessed the database server for half an hour. On the other hand, a service software module needs to access the database server through the client, but it can't ensure that there is at least one access every half an hour. This operation mechanism often causes the failure of the service software. In this example, it is hard to define whether a failure occurs in the situation of network connection loss. For the security software, the network is normal, but for the service software, the network is failed. In other words, because the network reliability analysis is not conducted from the application point of view, the definition of the network failure is unclear, and the traditional reliability parameters are not suitable in this case.

In order to evaluate the network reliability, individual applications should be analyzed first. Then, the traditional reliability analysis methods can be used for each unique application. Otherwise, it is impossible and/or useless to discuss the "failure" for a network with multiple applications.

Hence, the concept of *network application reliability* is proposed here. It is defined as the probability that a network will support multiple applications in a satisfactory manner. Here, an *application* is a usage mode under specific conditions for specific purposes. For example, network applications include the railway application in a transportation network, the e-mail application in a computer network, etc.

3. The Assessment Methodology

A complex network has three features: dynamic, random, and large in scale. It is easy to understand component reliability in network, but it is hard to evaluate the reliability of the network with multiple components under multiple applications.

The layered indices method (refer to Figure 1) is proposed here to assess the network reliability. The "index" here is a comprehensive value varying with time, like stock indices in a stock market. In this method, the comprehensive reliability

is determined by the reliabilities of all applications handled by the network and the application relationships. For each application, the components involved comprise a sub-network. The reliability for this application is determined by the components of this sub-network and the component relationships.

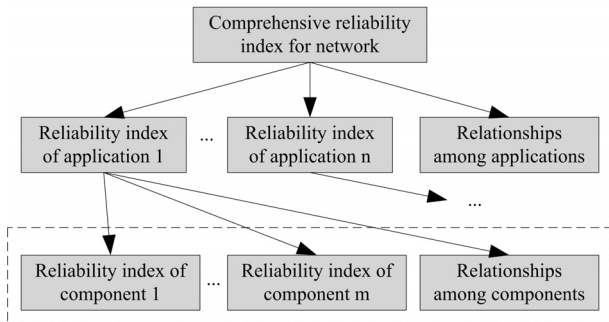


Fig. 1. The layered indices method for network reliability assessment

The reliability of a component is determined by whether the material, energy or information can be handled by this component timely, completely and correctly. The reliability index for a component is shown in Figure 2. For example, the parameter *connection rate* reflects the probability that the component is accessible, *delay* describes the time delay if any in completing the transmission, *loss rate* expresses the probability that the transmission is lost, and *error rate* indicates the probability that an erroneous transmission is received.

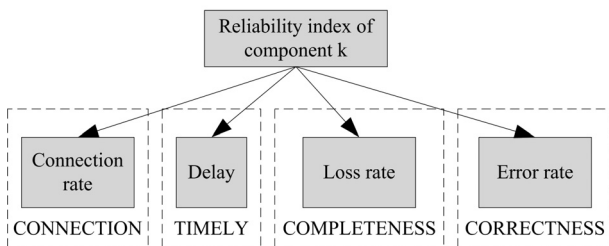


Fig. 2. The component reliability index

For different applications on the same network, the components involved may be different. The role of the same component may vary as it handles different applications. As a result, the parameters used to measure the reliability of the component may change.

3.1. Relationships

The “relationships among applications” and the “relationships among components” (refer to these blocks in Figure 1) are determined by network topology, operation mechanism, and service requirements. The relationship can be very complex, such as the application conflict example of the aviation enterprise network mentioned in Section 2. It can also be simple, for example, the common series parallel relationships, the connection between a client and a server in computer networks, the fault tolerance architecture in computer networks, and the connection between the main road and a feeder road in a transportation network.

3.2. The Layered Method

The *application* in this paper is a general reference to the use of the network. Therefore, a network application may be expressed in a hierarchy structure. The parameter system mentioned in this paper may also be represented by a layered structure. Here, the application reliability of each layer is decided by its son layer application reliabilities and their relationships.

Take the city transportation network as an example (refer in Figure 3). The following parameters may be considered: the reliability index of motor vehicle application (application 1), that of bicycle application (application 2), that of railway application (application 3), etc. For motor vehicle application, its reliability index can be broken down into: the reliability index of private car application (application 1.1), that of bus application (application 1.2), that of taxi application (application 1.3), etc.

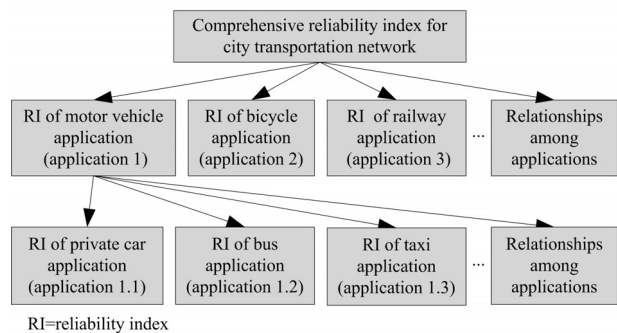


Fig. 3. The layered parameter system of city transportation network reliability

4. The Assessment for an Individual Application

According to the descriptions above, network reliability assessment can be divided into two levels: for an individual application and for multiple applications. The latter is the comprehensive assessment of the results obtained in the former (refer to Section 5). This section will focus on the assessment of an individual application. The analytical method is difficult to apply for large scale networks [17]. This study focuses on the testing and the simulation methods. Each of the two assessment method needs to solve the following common problems (as shown in Figure 4):

- Component selection: For a large scale network, it is time consuming to measure all its components. To simplify the measurement process, we may follow certain rules to select representative components. This procedure will reduce the computation time needed to evaluate the network reliability. The measures obtained on the selected components will provide very good approximations of those of the global network. These selected components will be called the measured components. The detailed description of this procedure will be provided in Section 4.1.
- Network simplification: For complex networks, we can utilize well known network simplification methods to simplify the network. These simplification methods include the utilization of the series structure, the parallel structure, the k-out-of-n structure, the delta-star transformation, and the star-delta transformation (see [31] for details on these simplification methods). Without these simplifications, it

will be too time consuming to evaluate the network using testing or simulation. This network simplification can be interpreted using *similarity theory* [26]. The reliability of the large scale network can be inferred by assessing the small scale one. The detailed content of this topic will be covered in Section 4.2.

- Application profile modeling: The profile refers to the description of the current application condition for the purpose of assessment [18]. Similar to the mission profile in the hardware assessment and the operation profile in software assessment, applications on the network form a corresponding application profile. For different application profile, the reliability of the same network may be different. Therefore, it is very important to construct the application profile accurately according to the use mode of the network. The detailed content of this topic will be provided in Section 4.3.
- Application reliability assessment: After the testing or simulation results are available, a feasible reliability computation model is needed to get a quantitative assessment of the network reliability for this application. The algorithm will be discussed in Section 4.4.

4.1. Component Selection

It is impossible and sometimes unnecessary to monitor all components in large scale networks. Therefore, a reasonable component selection method should be used to choose some representative components on behalf of the global network.

The component selection problem can be described as follows. For a network with N components, use an appropriate approach to select k components which can provide good representation of the characteristics of the whole network.

Random sampling is the first method used for this purpose. However, components selected by this method are lack of representation. Olston and Widom [19] proposed the adaptive sampling method based on unequal probability sampling according to node priority for a sensor network. Lin et al [14] developed the continuous adaptive sampling method for the sensor network, and provided geographical partition, bottom-up partition, and optimal partition methods to conduct stratified sampling.

Duffield [2] points out that the effectiveness of the selected sampling method is closely related to the purpose of sampling. Our purpose is assessment of the network reliability. Hence, we have selected the unequal probability sampling method here. The probability of selecting component i is determined by the component importance and its traffic. For components which

are more important and/or handles more traffic, the probability of selection is higher. The probability of selecting component i can be defined as

$$P_i = P \times \frac{\bar{T}_i \times I_i}{\sum_{i=1}^N (\bar{T}_i \times I_i)} \tag{1}$$

where, P_i is the probability of selecting component i ; P is the fraction of network components to be selected; \bar{T}_i is the average traffic handled by component i ; and I_i is the importance of component i .

4.2. Network Simplification

There is a need to simplify the network topology and network flow in order to reduce the computational load during testing or simulation. Random sampling [5] may also be used for this purpose. However, researchers have found that this method cannot provide a good representation of the original network characteristics [23]. Yang et al [27] put forward the *hub strategy*, which uses *degree* as an important criterion for node simplification. In the following, we describe network simplification using *similarity theory* [26].

Using the results of component selection as described in Section 4.1, the components are divided into two categories: measured components and non-measured components. The performance of the measured components will be monitored and evaluated while the non-measured components will participate in the functioning of the network but their performance will not be monitored. In a communication network, the parameters which have influence on network transmission include *bandwidth*, *buffer capacity* and *traffic*. The steps of network simplification for a communication network are given below:

- 1) Topological simplification. In a communication network, there are some special topologies, such as series structure, parallel structure, leaf structure, etc. The simplification principles for these special structures are given in Table 1. In this table, B is used to represent link bandwidth, C is for node buffer capacity, and T is for node traffic.
- 2) Network flow incorporation. The network flow should be incorporated as the topology is changed. There are three ways of incorporation: summation, choosing the minimum, and deleting both. The network flow incorporation methods of special topologies are shown in the last column of Table 1.
- 3) Network flow reduction. As described earlier, we will focus a smaller network through topological simplification. After

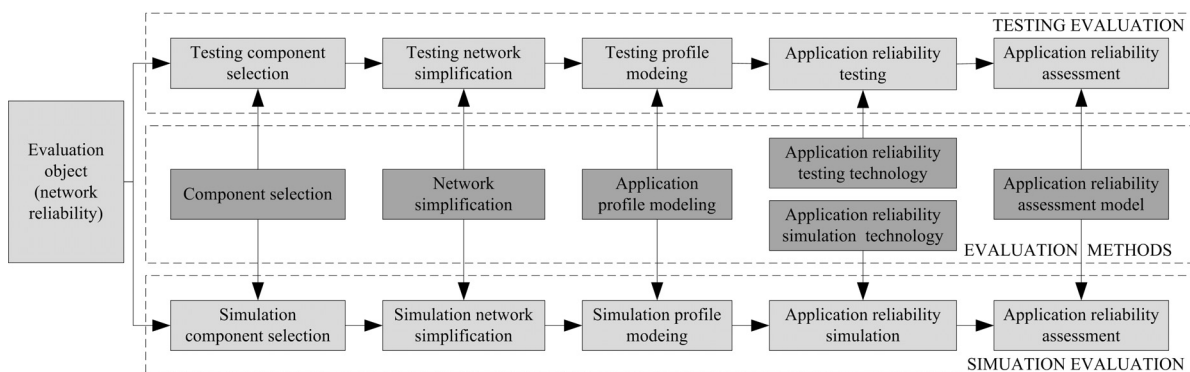


Fig. 4. Reliability assessment process for an individual application

Tab. 1. The network simplification principles for a communication network

Structure Type	The Original Topology	Communication Network Simplification	
		The Simplified Topology	Network Flow Incorporation
Series structure			<ul style="list-style-type: none"> ✓ Delete link bandwidth; ✓ Add node traffic together; ✓ Take the smaller buffer capacity.
Parallel structure			<ul style="list-style-type: none"> ✓ Delete link bandwidth; ✓ Add node traffic together; ✓ Take the smaller buffer capacity.
			<ul style="list-style-type: none"> ✓ Add link bandwidth together.
Leaf structure			<ul style="list-style-type: none"> ✓ Delete the link bandwidth; ✓ Add leaf traffic to the mother node traffic; ✓ Do not change node buffer capacity.
			<ul style="list-style-type: none"> ✓ Add link bandwidth together; ✓ Add leaf traffic together; ✓ Add leaf buffer capacity together.

○ Measured Node ● Non-measured Node

the network size is reduced, we need to reduce the traffic to be applied to the reduced network. Buffer capacity, bandwidth and traffic (refer to Table 2) are three parameters which impact the network transmission. They have two independent dimensions, Bit and second (s). In the last column of Table 2, C_2 , B_2 , T_2 refer to the original network buffer capacity, bandwidth and traffic. r_c , r_b , r_t are the similarity coefficients of the three parameters, and their values depend on network flow reduction requirement. Here, keep the time unit fixed, and reduce the information unit according to the the same ratio, $r_c=r_b=r_t$ is obtained. It means the reduction ratios of these three parameters are identical. In this way, the flow reduction results, namely C_1 , B_1 , T_1 , can be calculated. These are the network parameters to be applied to the reduced network.

Tab. 2. Similarity coefficients of communication network parameters

Parameter	Unit	Similarity Coefficient
Buffer Capacity	Bit	$r_c=C_1/C_2$
Bandwidth	Bit/s	$r_b=B_1/B_2$
Traffic	Bit/s	$r_t=T_1/T_2$

4.3. Application Profile Modeling

Application profile refers to operation conditions used to assess the “network application reliability” for a specific application, including the operation conditions of the application focused and those of other applications that have to be handled simultaneously by the same network. The application we are assessing is called the *foreground application*, and the others

are the *background applications*. As a well known network simulation software, *OPNET* [29] has defined types of users and applications. The application usage mode of each user is defined by the distribution functions of “*packet interarrival time*” and “*packet size*”. However, *OPNET* doesn’t provide a method to get the exact parameters for these distribution functions. We describe our application profile modeling method below.

- 1) Network application traffic monitoring. The network is monitored to get the traffic of both the foreground application and the background applications at each component. So far, various network traffic monitoring tools have been developed, such as website traffic monitoring, road traffic monitoring and so on. Some traffic monitoring tools can even provide the function to distinguish different applications, such as the NetFlow used in Cisco routers.
- 2) Network application traffic modeling. The traffic models are built for both the foreground application and the background applications at each monitored component according to the application traffic monitoring results. For communication networks, distribution functions of “cell interarrival time” and “cell size” can be established. For transportation networks, distribution functions of “vehicle interarrival time” can be set up. At present, a large number of traffic modeling methods have been developed, such as FARIMA model, ON/OFF model, FBM model, MWM model, etc [22].
- 3) Network application traffic generation. Network traffic generator is designed according to the application traffic modeling results. In a computer network, the traffic

generator is called “packet generator”, while in the communication network, it is named “call generator”. The network application profile is obtained by applying this kind of traffic generator in networks.

In addition, for reliability assessment, the stress level of the application profile can be divided into two situations. One is the normal traffic level used to evaluate the network reliability when it works under normal working conditions, and the other is the extreme traffic level used to evaluate the reliability of the network when it is overloaded.

4.4. Application Reliability Assessment

Before network reliability assessment, the failure criterion, which are the boundary values of certain parameters to determine whether failures have occurred, need to be specified. For different applications, the failure criterion are different. For example, delay threshold for video is 400ms, whereas that for file transmission is 60s [30].

Then, the reliability index is calculated for each individual application according to the testing and/or simulation results. The algorithm is shown in Figure 5.

```

IndividualApplicationComputation(n, m, TMT, δT, FC, TESTRESULT)
//input: n, m, TMT, δT, FC, TESTRESULT
//output: IARI(t)
for t ← δT to TMT step δT do
  for i ← 1 to n do
    Num(i, t) = "SELECT COUNT(*) FROM TESTRESULT WHERE Node=i AND REALTIME>t AND REALTIME<=t+δT"
    for j ← 1 to m do
      PFNum(j) = "SELECT COUNT(*) FROM TESTRESULT WHERE Node=i AND REALTIME>t AND REALTIME<=t+δT AND PV(j) outof FC(j)"
    endfor
    CRI(i, t) = [Num(i, t), PFNum(1), ..., PFNum(m)]
  endfor
  IARI(t) = f[CRI(1, t), ..., CRI(n, t)]
  Write IARI(t)
endfor
    
```

Fig. 5. Algorithm for individual application reliability

5. Comprehensive Assessment of Network Reliability

As the requirements for different applications may conflict with one another, the comprehensive assessment of network reliability should be implemented through the reliability indices for all network applications and the application relationships. The layered applications (refer to Section 3.2) can be described by application grouping (refer to Figure 6). Each application branch forms a group whose sequence number is marked by *AppGroup*, and the sequence number for each application in a group is marked by *Sequence*. The sequence number of the son application group is shown by the parameter *Leaf[AppGroup, Sequence]*. The sequence number of the mother group and the application in the group are indicated by *MotherGroup* and *MotherSeq*, respectively.

The algorithm for network comprehensive application reliability assessment is shown in Figure 7.

6. A Case Study

Now, let’s use a laboratory computer network as an example to explain the proposed network application reliability assessment method based on layered indices. The topology of the network is shown in Figure 8. In this network, PC₁ is used by the teacher, and PC₂~PC₉ are used by students.

6.1. Individual Application Reliability Assessment

First, the reliability assessment process for the FTP application is given. Similarly, reliability assessment for other applications, such as e-mail application, chat application, and so on, can be evaluated.

The operation mode of the FTP application is: PC₁-PC₉ can upload and download files from Sever, and PC₁-PC₉ cannot communicate with each other directly. Failure criterion for the FTP application are shown in Table 3.

1) Component Selection

In this case, all components may be involved in the FTP application. The hub is a transfer node which simply allows

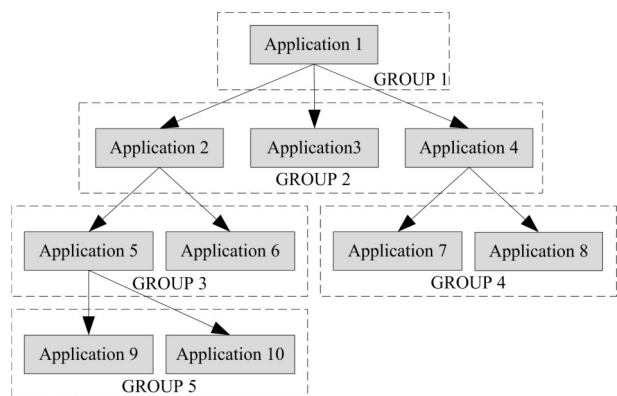


Fig. 6. The description of layered applications

```

NetworkApplicationComputation(TMT,  $\delta T$ , AppNum, Leaf, ARI)
//input: TMT,  $\delta T$ , AppNum, Leaf, ARI
//output: RI(t)
for  $t \leftarrow \delta T$  to TMT step  $\delta T$  do
    AppGroup=1
NextGroup:
    for  $j \leftarrow 1$  to AppNum(AppGroup) do
        if Leaf(AppGroup, j) > 0
            MotherGroup=AppGroup
            MotherSeq=j
            AppGroup=Leaf(AppLeve, j)
            goto NextGroup
        endif
    endfor
    ARI(MotherGroup, MotherSeq, t)=[ARI(AppGroup, 1, t), ..., ARI(AppGroup, AppNum(AppGroup), t)]
    AppGroup=MotherGroup
    Leaf(MotherGroup, MotherSeq)=0
    if AppGroup < 1
        goto NextGroup
    else
        RI(t)=ARI(1, 1, t)
    endif
Write RI(t)
endfor
    
```

Fig. 7. Algorithm for network comprehensive application reliability assessment

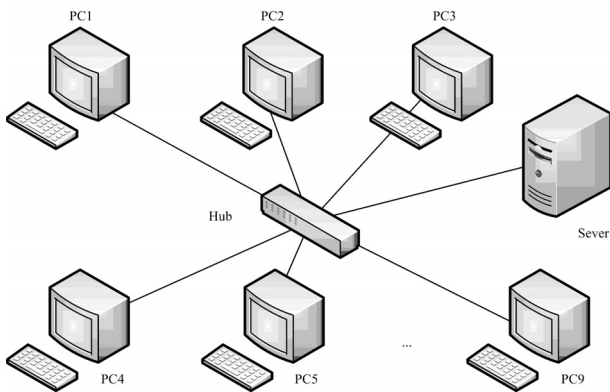


Fig. 8. Laboratory network topology

traffic to go through, so it is out of the scope of our discussions. Therefore, the population is 10, including the server and 9 PCs. Even though the network is pretty small, we will still illustrate the process of component selection in order to simplify the network monitoring.

Let the sampling fraction $P=0.40$. We can run the network and monitor its FTP traffic. The traffic handled by each component can be measured. In this network, assume that server is twice as important as PC1 which is used by the teacher, and PC1 is twice as important as any other PC which is used by a student. According to equation (1), combining with the component traffic percentage and the importance percentage (refer to Table 4), the probability of each component being selected can be calculated (refer to Table 4).

With these probabilities of selection, components can be selected based on the Monte-Carlo method, and the following samples are obtained: Server, PC₁, PC₄ and PC₆. These compo-

Tab. 3. Failure criterion for the FTP application

Failure Type	Failure Criterion	Description
Function failure	Connection loss criterion	A PC is disconnected from the Sever
Parameter failure	Transmission delay criterion	Delay threshold: 15s
	Transmission loss criterion	PLR (packet loss rate) threshold: 0%
	Transmission error criterion	BER (bit error rate) threshold: 0%

Tab. 4. The sampling parameters

Component	Sever	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
Importance percentage	0.29	0.14	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Traffic percentage	0.50	0.11	0.05	0.03	0.03	0.05	0.22	0.01	0.00	0.00
Probability of selection	0.77	0.08	0.02	0.01	0.01	0.02	0.08	0.00	0.00	0.00

nents then become the measured components while the rest are the non-measured components.

2) Network simplification

The measured and the non-measured components are shown in Figure 9(a) according to the component selection results. Then network simplification is conducted based on the steps in Section 4.2:

a) Topology simplification

Figure 9(a) is a typical star topology, so its topology can be simplified in accordance with the topology simplification principles in Table 1. Combining all the non-measured nodes into one, and the simplified topology is shown in Figure 9(b).

b) Network flow incorporation

In the simplified topology shown in Figure 9(b), according to the flow incorporation principles in Table 1, the node traffic and the buffer capacity of the non-measured components, namely, PC₂, PC₃, PC₅, PC₇, PC₈ and PC₉, are merged into PC_{in}, and the bandwidth between these non-measured components (including PC₂, PC₃, PC₅, PC₇, PC₈ and PC₉) and the hub are also combined together.

It should be noted that, the network usage is much lower than the network physical capacity in this LAN, even after the combination of the 6 non-measured nodes. Therefore, the hardware configuration doesn't need to be changed in real testing. As network flow is not too heavy, we don't need to reduce the flow and the configuration parameters such as traffic, bandwidth and buffer capacity.

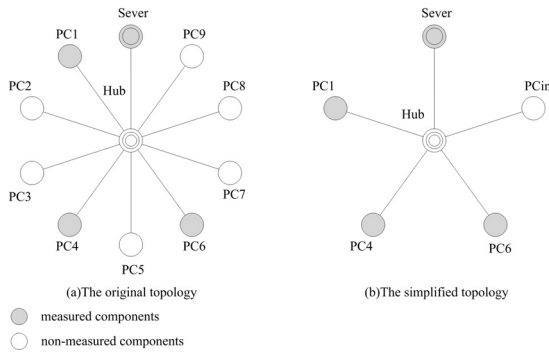


Fig. 9. Network simplification

3) Application profile modeling

In this computer network, "application type", "packet interarrival time" and "packet size" are three key factors in application profile modeling. According to Section 4.3, the application profile modeling method for computer networks is listed below:

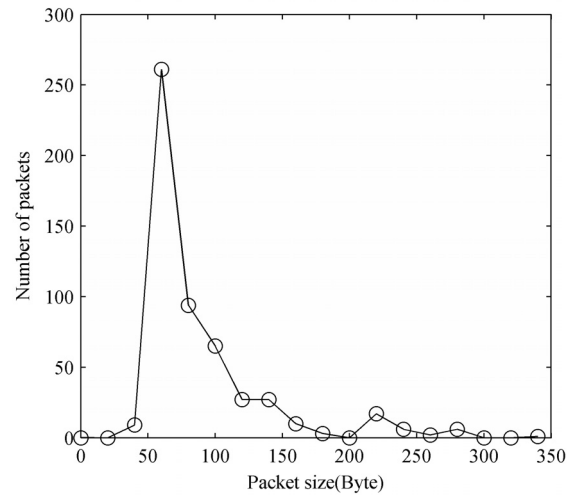
a) Network traffic monitoring

There are many successful business software packages such as *Netflow Tracker*. Such traffic monitoring software can distinguish different applications through TCP/UDP port number (FTP port number is 21), and provide statistics of "packet interarrival time" and "packet size" (refer to Figure 10).

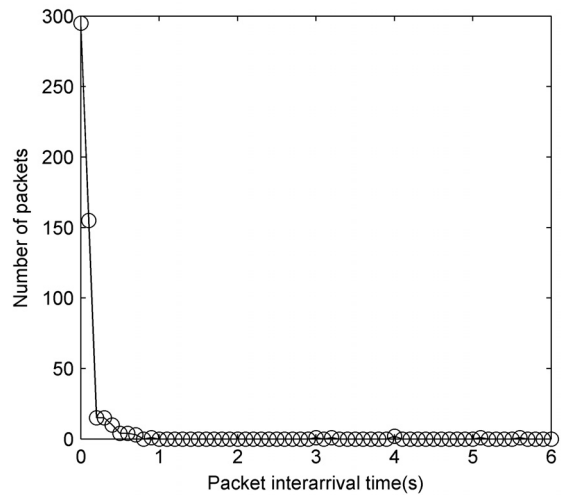
According to different application statistics, "packet interarrival time" and "packet size" of both the foreground FTP application and other background applications can be obtained.

b) Network traffic modeling

The distribution functions of "packet interarrival time" and "packet size" of the FTP traffic and other background traffic can be constructed according to the traffic statistics collected. In this computer network, "packet size" usually follows the normal distribution, application traffic often follows the Poisson distribution, and "packet interarrival time" usually follows the exponential distribution [20]. After fitting these distributions using the data collected, we obtained the following results: the "packet size" of the FTP application on the Sever follows the normal distribution with $\mu=66$ bytes and $\sigma=22$ bytes; the "packet interarrival time" on the server follows the exponential distribution with $\mu=0.18$ s; and so on.



(a) "Packet size" distribution



(b) "packet interarrival time" distribution

Fig. 10. The traffic monitoring results of the FTP application on the Server

c) Network traffic generation

According to the application profile models, a packet generator is used to generate both foreground traffic and background traffic in this network. There are many business packet generators, such as packet generator in *Sniffer Pro*. However, most of them cannot distinguish different applications, and can only send packets in a fixed interval with a fixed quantity.

In order to solve this problem, VC socket is used to program a packet generator which can distinguish different applications. Through “packet interarrival time” and “packet size” sampling, the testing profile can be generated.

4) Testing

Network measurement includes active measurement and passive measurement. In order to generate the network application profile, the active measurement is usually used. At present, there is no business software for network application reliability measurement. But several sniffer software tools, such as *Sniffer Pro*, *JanSee*, etc, can provide some performance monitoring results.

5) Reliability Assessment of the FTP Application

The reliability parameter system for the FTP application is shown in Figure 11. The FTP application reliability is determined by the reliability indices of the measured components and their relationships. The component reliability indices are determined by whether the FTP application can be implemented timely, correctly and completely (or whether the transmission meets its failure criterions).

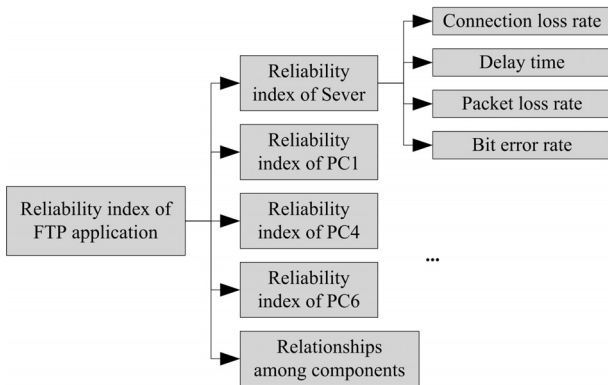


Fig. 11. Parameter system for the FTP application

The FTP application reliability can be evaluated through the algorithm in Figure 5. Firstly, the component reliability index can be calculated by

$$RI_{ij}(t) = \omega_{CLR} \frac{CLRN_{ij}(t)}{N_{ij}(t)} + \omega_D \frac{DN_{ij}(t)}{N_{ij}(t)} + \omega_{PLR} \frac{PLRN_{ij}(t)}{N_{ij}(t)} + \omega_{BER} \frac{BERN_{ij}(t)}{N_{ij}(t)} \quad (2)$$

where, $RI_{ij}(t)$ refers to the reliability index for component j under application i by time t ; $CLRN_{ij}(t)$, $DN_{ij}(t)$, $PLRN_{ij}(t)$ and $BERN_{ij}(t)$ are the number of times that the connection loss rate, delay time, packet loss rate and bit error rate exceed their thresholds respectively; $N_{ij}(t)$ is the number of packets of application i flowing through component j by time t ; ω is the importance weight of the four performance measures, and $\omega_{CLR} + \omega_D + \omega_{PLR} + \omega_{BER} = 1$. For the FTP application, the measure timely is more important than the other three measures, thus, we have selected $\omega_D = 0.4$, and $\omega_{CLR} = \omega_{PLR} = \omega_{BER} = 0.2$.

The reliability index of the FTP application can be calculated as follows:

$$RI_i(t) = \sum_{j=1}^n \omega_j RI_{ij}(t) \quad (3)$$

where, $RI_i(t)$ refers to the reliability index for application i by time t ; $\omega_i (i = 1, 2, \dots, n)$ is the importance of each component, and $\sum \omega_i = 1$. The most important component in the network is the server, followed by PC₁ as it is used by the teacher. Hence, let $\omega_{server} = 0.5$, $\omega_{PC1} = 0.3$ and $\omega_{PC4} = \omega_{PC6} = 0.1$.

6.2. Comprehensive Assessment of Network Reliability

The network application reliability can be evaluated comprehensively through the results of individual application reliability indices. The applications in this case include the FTP application, the e-mail application, and the chat application. The parameter system for network application reliability is shown in Figure 12.

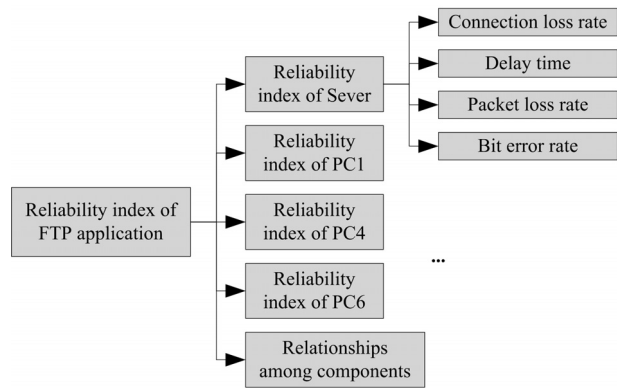


Fig. 12. Parameter system for network application reliability assessment

As shown in Figure 12, some applications may use more than one protocol in the application layer. For example, the e-mail application includes the SMTP protocol and the POP protocol. For different protocols, the failure criterion may be different, so multiple application reliability indices can be calculated according to the layered method in Section 3.2 and the algorithm in Section 5. Here, the relationships among applications are described by the weighting method.

For the e-mail application, the reliability index can be calculated by

$$RI_{e-mail}(t) = \omega_{receive} RI_{receive}(t) + \omega_{send} RI_{send}(t) \quad (4)$$

where, $RI_{e-mail}(t)$, $RI_{receive}(t)$ and $RI_{send}(t)$ refer to the reliability index for the e-mail application, the e-mail receiving application, and the e-mail sending application, respectively; $\omega_{receive}$ and ω_{send} are the weights of the e-mail receiving and the e-mail sending applications, and $\omega_{receive} + \omega_{send} = 1$. For the e-mail application, the importance of receiving and sending are the same, so let $\omega_{receive} = \omega_{send} = 0.5$.

The comprehensive network application reliability index for this network is calculated by

$$RI(t) = \omega_{\text{FTP}} RI_{\text{FTP}}(t) + \omega_{\text{e-mail}} RI_{\text{e-mail}}(t) + \omega_{\text{chat}} RI_{\text{chat}}(t) \quad (5)$$

where, $RI(t)$, $RI_{\text{FTP}}(t)$, $RI_{\text{e-mail}}(t)$, $RI_{\text{chat}}(t)$ refer to the reliability index for the whole network, the FTP application, the e-mail application, and the chat application, respectively; ω_{FTP} , $\omega_{\text{e-mail}}$ and ω_{chat} are the weights of the three applications, and $\omega_{\text{FTP}} + \omega_{\text{e-mail}} + \omega_{\text{chat}} = 1$. In this case, the importance of the e-mail application is a little higher than the other two applications, so let $\omega_{\text{e-mail}} = 0.4$ and $\omega_{\text{FTP}} = \omega_{\text{chat}} = 0.3$.

7. Comments and Conclusion

In early 1989, a network reliability analysis method was proposed by John [12] based on the component (including hardware and software) reliability and the topology. But this method considered only the network connection reliability without the measurement of the application reliability. Yin et al [28] presented a method to efficiently estimate the real time network reliability through the component reliability. However, this method considered the usage without the application profile considerations, so it can't be applied in the reliability assessment under certain application conditions considered in this paper. Jereb and Kiss [13] proposed a network reliability calculation method through the concept of layered network in one of Nokia company's research reports. The method aimed to solve the "state explosion" problem by reducing the number of unnecessary states. However, this method is lack of the consideration of the operational profile and the relationship among applications.

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In this paper we have proposed a methodology for network application reliability assessment base on the layered indices. We have emphasized that network reliability may vary with applications that are handled by the network. The proposed network reliability assessment method has two steps: first, assessing the individual application reliability (involve four key technologies, including component selection, network simplification, application profile modeling and application reliability assessment); second, assessing the network comprehensive reliability according to the layered applications. Finally, the steps of this method are fully explained through the assessment of a laboratory computer network.

In general, the contributions of this paper are:

- A scientific and practical network application reliability assessment method is put forward. A case study is given to demonstrate this method.
- The layered indices assessment method is explained. The coupling relationships of network reliability parameters are taken care of through indexation.
- The component selection and network simplification technologies are used. With these technologies, the workload of the assessment can be reduced significantly, and the computation efficiency can be improved.
- The method of building application profile is given, and the assessment accuracy can be improved.

At present, the relationships among components and among applications are not described sufficiently. Also, the method is not applied in network reliability simulation. Our future work will focus on solving these problems.

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