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A new forwarding address for next generation networks*

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Abstract: The forwarding address plays an important role in constructing a communication network. In this paper, a new forwarding address suitable for next generation networks named the vector address (VA) is proposed which is different from the forwarding address coding methods of current networks. The characteristics of the VA are analyzed. Complex network theory and a theoretical analysis method are introduced to study the average address length of the VA when used to construct a global network. Simulation experiments in a practical network topology model are carried out to validate the results. The results show that not only can the VA construct a simpler, more secure, and more scalable network, but it also can accommodate many more users than an Internet Protocol (IP) network with the same address length.

Key words: Next generation networks (NGN), Forwarding address, Vector address (VA), Complex network
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1 Introduction

There are many kinds of network addresses in communication networks, e.g., Internet Protocol (IP), asynchronous transfer mode (ATM) terminal, and ATM virtual path identifier/virtual channel identifier (VPI/VCI) addresses. These addresses differ in their properties and purposes. Some are used to identify node machines, while others are used for routing and switching. Some which are easy to remember are used by people, while others which are convenient for storing and processing are used by machines. Among these addresses there are two basic kinds which are most important: identification addresses, which are used to identify a network node and are usually applied in the control plane, and forwarding addresses.

A forwarding address is used in the data plane for the purpose of switching by a forwarding device. It occupies a field in a data packet and is used to determine the output-interface to which the packet will be sent by the forwarding device. A good forwarding address should be suitable for forwarding data packets at high speed and in a nutshell.

Based on the above definitions, in ATM networks, an ATM terminal address is a kind of identification address and a VPI/VCI address is a kind of forwarding address. But in IP networks, the IP address plays the roles of both the identification address and the forwarding address. IP and ATM VPI/VCI addresses represent two kinds of typical forwarding addresses in current networks. An IP address is coded by numbering node machines in the whole network, a coding method which can therefore be called node-based. An ATM VPI/VCI address is coded by numbering virtual links in a communication link, a method which can therefore be called link-based.

In view of the problems of poor scalability, low security, and complex forwarding devices in IP and ATM networks, in this article a new kind of forwarding address is proposed, called the vector address (VA) (Liang, 2009a; 2009b). The VA differs from node- and link-based coding methods, as it is coded by numbering the interfaces of a node machine, i.e.,

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an interface-based coding method. A network constructed based on this kind of forwarding address is called a vector network (VN) (Liang *et al.*, 2008; Zhang and Liang, 2008; 2010). A forwarding device in the VN is named a vector switch (VS) (Wang *et al.*, 2008; Wang and Liang, 2008).

In this paper, first, the necessary background material and related works are introduced briefly. The primary work of this research is to analyze the characteristics of the VA. Our analysis will focus on the average address length of the VA when being used to construct a global network. The purpose of this research is to provide theoretical support to enable VA to be applied in practical communication networks.

2 Background

2.1 Calling and routing

In the VN, three kinds of identification are used. The first is the identity (ID), which is unique to a node in the network. The second is the locator, which denotes the location of a node in the network. The third is the switching label, which is similar to the VPI/VCI in an ATM network. The switching label is used to forward packets, so it is also called a forwarding address in this paper. In the VN, the vector address or VA is used as a switching label. The resolution from an ID to the locator is completed through a calling process, and the resolution from a locator to the switching label is completed through a routing process. The functions of the resolution process or the calling and routing process are distributed over the whole network, which is different from the domain name service resolution process in an IP network. The processes can avoid the unreliability arising from a centralized service.

2.2 Mobility

In the initial design stage of IP networks, mobility support problems were not considered, so traditional IP networks could not support the movement of nodes. To solve the mobility problem, the mobile IP protocol was proposed. However, it has brought many other problems such as address wastage, triangular routing, and increased handoff delay. The VN is a new kind of network in which the mobility support problem has been considered adequately in the initial design stage. The philosophy to separate the ID, locator, and switching label is adopted in the VN. This is a very important idea which provides a basis for dealing with mobility support related problems. By introducing the concepts of ID, locator, and switching label, the different functions of a network node are separated. The ID identifies the identity of the node and is used in transport layer session management. As the location identification of a node, the locator is used in the routing process. The switching label or VA is used in the data forwarding process. In the VN, if a node moves, only the VA of the node needs to change and the ID of the node remains unchanged. Therefore, the movement of a node is transparent to the transport layer of the node.

2.3 Multicast

The IP multicast mechanism is usually used in current networks. However, IP multicast cannot be used in the VN because the VN is based on a new kind of address coding scheme. Therefore, we have designed a new kind of multicast method for the VN. First, the multicast sender computes a multicast distribution tree to multiple multicast receivers which regard the multicast sender as the root, the multicast routers as branches, and the multicast receivers as leaves. Second, the multicast sender executes a segmented routing process according to the structure of the multicast distribution tree and obtains multiple VAs as a result. The segmented routing method is specially designed for this multicast method in which the routing path is limited to going along the multicast distribution tree. Finally, the multicast sender integrates the obtained multiple VAs to form a kind of dendriform VA and sends out the multicast packets with the dendriform VA as the destination. This kind of dendriform VA is a special VA design for multicast by which a multicast router can read out multiple element addresses and forward multiple copies of the packet along the tree branches.

2.4 Multi-homing

The multi-homing support problem is very similar to the mobility support problem. It is hard to support multi-homing in an IP network. The separation of the ID, locator, and switching label adopted in the VN makes it easy to support multi-homing. In the VN, if part of the network suffers from failures, only the VA needs to change to switch to another transmission path. The ID of the node remains unchanged. Therefore, network failures and the switching of the transmission path are transparent to the transport layer which will not break the survivability of the session.

2.5 Multi-path

Multi-path transmission can be more efficient than single-path transmission. There have been several proposals for multi-path route-computation and novel routing methods. However, the fact that these developments have not triggered widespread deployment shows that the key problem is not a lack of algorithms and protocols, but an architectural problem. The VN can support multi-path in its architecture and at very low cost. The VN is a kind of connection-oriented network. The connections are established through the calling and routing processes. Each connection is denoted by a VA which corresponds to a path in the network. Therefore, it is easy to establish multi-path connections with multiple VAs through a multi-path route-computation algorithm in the routing process. As already stated, the VA is a kind of address based on the interface numbers of forwarding devices. The VA, i.e., the connection information, needs to be stored only in the terminal devices and not in the forwarding devices. Therefore, almost no network resource consumption is needed to support multi-path in the VN.

3 Related works

The VA proposed in this paper adopts two basic ideas. One is path-based addressing; the other is addresses with local semantics. Both of these ideas have been developed in related research works. For path-based addressing, the typical example is IP source routing (RFC 791:1981; RFC 2460:1998). When source S wants to send a packet to destination D through intermediate nodes M and N, it creates a packet that includes the sequence $<S, M, N, D>$. This sequence can be viewed as a path-based address. S sends the packet to the first component, M, which sends the packet to the next component, N, and so on. Other proposals adopting path-based addressing include Pip (Francis, 1993), SIPP (Francis and Govindan, 1994), and TUBA (Katz and Ford, 1993). The idea of addresses with local semantics is widely used in virtual-circuit networks, such as X.25 (CCITT X.25:1977), Frame Relay (Smith, 1993), ATM (McDysan and Spohn, 1998), and multi-protocol label switching (MPLS) (RFC 3031:2001). In MPLS for example, a label may have only local semantics. It may be understood only by the node that is supposed to read and switch it.

Recently, the two ideas have been combined in some research works. These proposals include translating relaying Internet architecture integrating active directories (TRIAD) proposed by Cheriton and Gritter (2000), BANANAS proposed by Kaur *et al.* (2003), new Internet routing architecture (NIRA) proposed by Yang (2003), and location independent resource accounting (LIRA) proposed by Stoica and Zhang (1998). TRIAD provides a kind of path-based addressing using a shim protocol called Wide-area Relay Addressing Protocol (WRAP). The components of a WRAP address are hierarchical character-string names which have only local semantics. But when an intermediate node receives a WRAP packet, the node has to interpret the local name and translate it to the IP version 4 (IPv4) address through a relay table. In BANANAS, a path is encoded as a short hash of a sequence of globally-known identifiers called PathID. An alternative hash function has been developed to use an index-based encoding scheme that is a concatenation of link ID indices at nodes. The routers maintain an index table that maps the link index to the link interface IP address. On receiving a packet, the router extracts the link index of the outgoing interface from the PathID field in the packet header and uses the index table to forward the packet on the appropriate link. NIRA aims at providing end users the ability to choose domain-level routes, which are sequences of domains through which a packet traverses. It includes a hierarchical provider-rooted domain-level addressing scheme and a route representation method based on the addressing scheme. In LIRA, a path is encoded as the XOR of router IDs along the path, and is processed along the path using a series of XOR operations.

The VA proposed in this paper also combines the two ideas. But it has the following differences compared with the above proposals. First, it has been developed for a different purpose. While TRIAD is for content distribution, BANANAS for multi-path routing, NIRA for providing end users the ability to choose domain-level routes, and LIRA for service differentiation, the VA is proposed to construct a new kind of communication network, i.e., the VN, which can substitute for the current IP network. Second, and more importantly, an interface number based coding method is adopted in the VA to avoid the need of lookup address tables for the routers. This cannot completely be achieved using the other methods. The index-based encoding scheme in the BANANAS proposal is close to our VA coding method, but the routers still use an index table to map link indices to link interface IP addresses.

4 Coding method for the vector address

The network shown in Fig. 1 will be used as an example to explain the definition of the VA. The squares and circles labeled from *A* to *K* are nodes and the solid lines between pairs of nodes are links. Each node has a number of interfaces numbered from 1, which is called the interface number. A path in the network can be described by a node sequence. For instance, {*A*, *G*, *I*, *J*, *C*} is a path from node *A* to node *C*. A path can also be described by a sequence of output interface numbers. For example, path {*A*, *G*, *I*, *J*, *C*} can be denoted as '1143' where digits 1, 1, 4, and 3 correspond to the output interface numbers of nodes *A*, *G*, *I*, and *J* respectively, on the path. The destination node *C* is excluded. The digital string '1143' is exactly a VA from nodes *A* to *C*. Formally, we define a VA from a source node to a destination node as a sequence of output interface numbers of nodes along a path from the source to the destination. The interface numbers in the sequence look like direction indicators guiding the packets to arrive at the destination, step by step. Each interface number in the VA is called an element address.

In practice, a VA is expressed in binary format. Taking '1143' as an example, the results are listed in Table 1. In the second column of this table, the output interface numbers of nodes *A*, *G*, *I*, and *J* are listed. The quantity of interfaces at each node is given in the third column. According to the quantity of interfaces, the number of bits to code these interfaces in binary format in each node can be deduced and is listed in the fourth column. In the last column, the element address of each node in binary format is given. Thus, the final VA in binary format is '101100011'.

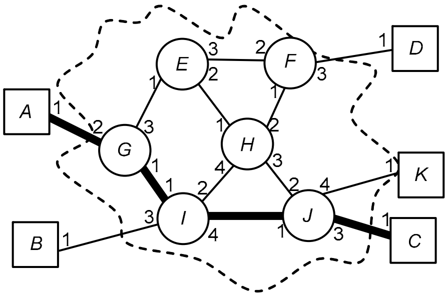

Fig. 1 Definition of the vector address

The squares and circles labeled from *A* to *K* are nodes and the solid lines between pairs of nodes are links. Each node has a number of interfaces numbered from 1, which is called the interface number

Table 1 Binary format of an example vector address

Node	Interface number	Quantity of interfaces	Number of bits	Binary coding
A	1	1	1	1
G	1	3	2	01
I	4	4	3	100
J	3	4	3	011

The following data forwarding method is applied in the VN. When a VS receives a data packet from one of its input interfaces, it extracts the first element address of the VA from the packet, deletes it from the packet, and sends the packet to the output interface pointed by this element address.

5 Characteristics of the vector address

According to the above definition, it can be deduced that the VA has the following characteristics.

1. Infiniteness. The number of VAs between a source and a destination is not only one, but is infinite. The VA from *A* to *C* (Fig. 1) can be '1143', '11233', '13233', '132443', and '132413233'. Obviously, among the five listed VAs, the first is the shortest and the last is the longest due to the existence of a cycle. There may exist arbitrary local cycles in the path of a communication network, so the numbers of VAs from *A* to *C* are countless. In practice, we usually adopt the shortest path or a path close to the shortest. But some cycles may be useful for encryption.

2. Non-readability. In the forwarding process in the VN, a VS can understand only its own element

address. It cannot obtain the frontal element addresses and cannot understand the posterior element addresses. For instance, in Fig. 1, when source *A* is sending a packet to destination *C* using VA '1143' ('101100011' for binary format), the VS *G* can see only the address '01100011', because the frontal element address '1' belonging to source *A* has been used and deleted. Furthermore, for '01100011', *G* knows only that the first 2-bit belongs to itself and it cuts the element address '01' for use. The remainder address '100011' may have various combinations such as '10+0011', '100+011', and '10+001+1', so it is impossible for *G* to understand how to split it.

3. Encryption property. A VA can be encrypted because any VS in the data transmission path can complete its forwarding task as long as it knows how to decrypt its own element address. So long as the source node establishes a secret key with each VS in the path through negotiation before communication begins, the communication with the address completely encrypted can be realized. With regard to non-readability, the VA has quite a strong ability to realize encryption communication. Indeed, not only can the transmitted data be encrypted, but the identities of the communication participants on both sides can also be protected.

4. Relativity. The meaning of a VA is relative to the source. If a VA is given without the information about the source, its meaning is ambiguous. For example, in Fig. 1, for the same VA '1143', relating to source *A*, the destination is *C* and the defined path is {*A*1, *G*1, *I*4, *J*3}; but relating to source *D*, the destination is *B* and the defined path is {*D*1, *F*1, *H*4, *I*3}.

5. Variability in address length. The length of a VA is variable and may be any length, as required.

6. Obtaining routing information. A VA defines a path in the network and contains routing information useful for the VSs. A VS can obtain the routing information from the VA directly.

These characteristics of the VA give it the following advantages in the VN compared with IP and ATM networks: (1) The network based on VA is more secure than the current networks. (2) The network is simpler. It does not require lookup address tables or record any information for network connections. As a result, the forwarding devices in the VN are greatly simplified. (3) The network is more scalable. It can be freely extended because there are no problems of address duplication or address exhaustion. Two independently constructed networks can be combined directly to form a larger network.

6 Average length of the vector address

The length of the VA is variable. Furthermore, the address length becomes a little shorter as one data packet is forwarded a hop ahead in the data transmission process. When the packet reaches the destination, the address length changes to zero. Intuitively, the length of the VA is longer when the network size is larger, and vice versa. The length of the VA has a direct impact on the efficiency of communication link resources, so it is a key factor when deciding if VA can be applied in practical communication networks.

In this section, the average length of the VAs when used to construct a global network is investigated. First, an estimation model is proposed. Next, complex network theory (Wang *et al.*, 2006; He *et al.*, 2009) and a numerical simulation method are introduced to calculate the average length of the VAs.

6.1 Estimation model

A communication network can be denoted as a graph which is made up of a set of vertexes and a set of edges. In the estimation model, only the non-directional and non-weighted graph is taken into account and it is supposed that there are no duplicated edges or self-loops.

The distance d_{ij} between two vertexes *i* and *j* in a network is defined as the number of edges on the shortest path which connects vertexes *i* and *j*. The average path length of a network *L* is defined as the average distance between any two vertexes in the network. That is,

$$L=\frac{2}{N(N-1)}\sum_{i>j}d_{ij}, \tag{1}$$

where *N* is the number of vertexes in the network.

The degree k_i of vertex *i* in a network is defined as the number of other vertexes that are connected to vertex *i*. The average degree of vertexes in a network *K* is defined as the average value of the degrees of all vertexes in the network. That is,

$$K = \frac{1}{N}\sum_{i=1}^{N} k_i. \tag{2}$$

The distribution of the degrees of vertexes in a network can be described by the distribution function $P(k)$, which denotes the probability of a randomly selected vertex whose degree is exactly equal to k.

When a VA is used as a forwarding address, its length depends on two factors: the number of element addresses comprising the VA and the length of each element address. The number of element addresses depends on the distance between the source and the destination. The length of each element address depends on the number of interfaces of each vertex on the communication path, i.e., the degree of each vertex. In our estimation model, it is supposed that the average length of each element address is b and that b is an integer. If the interfaces of each vertex are numbered from 1, the following equation can be deduced:

$$2^b - 1 \geq K > 2^{b-1} - 1. \tag{3}$$

That is,

$$b = \lceil \log_2 (K+1) \rceil. \tag{4}$$

Considering that the first element address of any VA will be deleted before the source sends out a packet, the average number of element addresses in a VA is $L-1$. Furthermore, considering that the related element address will also be deleted when the packet passes through each vertex, the average length of the VAs can be calculated using the following equation:

$$V = \frac{b(L-1)}{2}. \tag{5}$$

6.2 Calculation results

The practical communication network is a typical kind of complex network. In complex network theory, a lot of network topology models have been proposed. The ER random graph (Erdős and Rényi, 1960; Dellamonica *et al.*, 2008), WS small-world network (Watts and Strogatz, 1998; Zou *et al.*, 2009), and BA scale-free network (Barabási and Albert, 1999; Li *et al.*, 2008) models will be used in this study to calculate the average length of the VAs when used to construct a global network.

6.2.1 ER random graph model

In ER random graph models, the probability that there exists an edge between any two vertexes is assumed to be p. A threshold of p denoted as p_c is equal to $(\ln N)/N$, where N is the number of vertexes in the network. The average degree of vertexes (K) and the average path length of network (L) can be calculated using the following equations:

$$K = p(N-1) \approx pN, \tag{6}$$

$$L = \frac{\ln N}{\ln K}. \tag{7}$$

We set N to be the maximal number of nodes that can be accommodated in the IPv4 network, i.e., $N=2^{32}$. Then p_c is equal to 5.2×10^{-9}. According to Eqs. (6), (7), (4), and (5), K, L, and the average length of the VAs V can be calculated under different probabilities which vary around the threshold p_c. The calculation results are shown in Fig. 2.

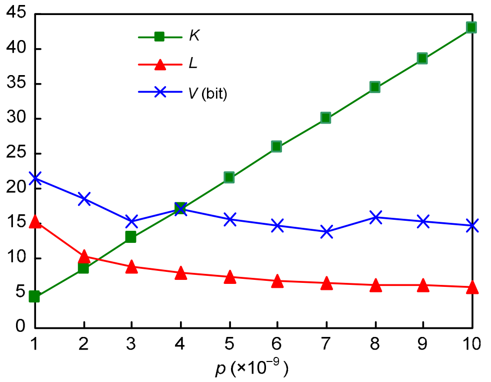

Fig. 2 Variation in V, K, and L in relation to p in the ER random graph model

When $N=2^{32}$, V fluctuates around 15 bits with the maximum value being about 21 bits, which is far less than the 32-bit length of an IPv4 address. In a typical network configuration with K being kept between 6 and 14, L varies between 13 and 8, and V varies between 20 and 15 bits. In addition, the increase in probability p will result in a linear increase in K, but will not lead to a distinct change in V.

We now try to increase the value of N in the case of $p=p_c/3$, which has no distinct impact on V and can ensure that K is kept in a typical network configuration. The parameters K, L, and V have been re-calculated. The results are shown in Fig. 3.

V increases with N in the typical network configuration. When N reaches 2^{64}, V is close to the 32-bit length of an IPv4 address.

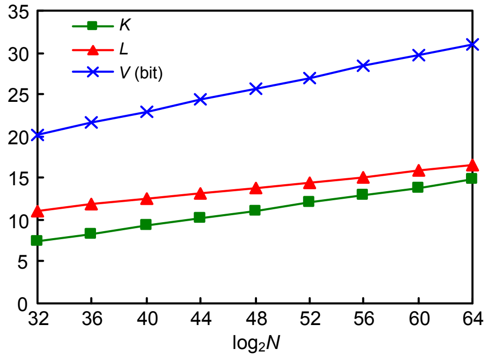

Fig. 3 Variation in V, K, and L in relation to N in the ER random graph model

6.2.2 WS small-world model

Before describing the WS small-world model, we will introduce a kind of regular network model called the nearest-neighbor coupled network. In this model, all N vertexes form a loop. Each vertex is connected by only its left $J/2$ and right $J/2$ neighbor vertexes, where J is an even number. The degree of each vertex in this model is exactly J. The WS small-world model can be constructed on the basis of a nearest-neighbor coupled network. Each edge in the nearest-neighbor coupled network is reconnected with probability q, with one vertex remaining unchanged, and another vertex changing to a randomly selected vertex in the network. When q=0, it is a completely regular network. Accordingly, when q=1, it is a completely random network. The value of q can be adjusted to control the transition from a completely regular to a completely random network.

According to the above construction method, in the random reconnection process from a nearest-neighbor coupled network to a WS small-world model, the total degree of all vertexes in the network remains unchanged, so the average degree of vertexes also remains unchanged. That is,

$$K = J. \tag{8}$$

The equation to calculate the average path length in the WS small-world model is as follows (Newman and Watts, 1999):

$$L = \frac{2N}{J} f(NJq/2), \tag{9}$$

where the function $f(\cdot)$ can be described using the following approximate equation (Newman *et al.*, 2000):

$$f(x) \approx \frac{1}{2\sqrt{x^2+2x}} \operatorname{arctanh}\sqrt{\frac{x}{x+2}}. \tag{10}$$

The number of vertexes N is set to be 2^{32}. The value of K or J is selected from 6 to 14 corresponding to the average number of interfaces in the typical network configuration. The value of q is selected from 0.025, 0.05, 0.075, and 0.1. According to Eqs. (8), (9), (10), (4), and (5), the average length of the VAs V can be calculated. The calculation results are shown in Fig. 4.

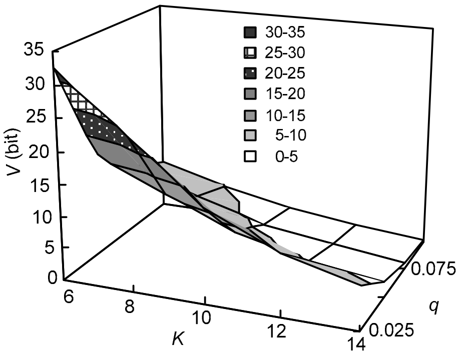

Fig. 4 Variation in V in relation to K and q in the WS small-world model

V increases when the parameters q and K decrease in the typical network configuration. When q=0.025 and K=6, V arrives at its maximum value, which is approximately equal to 32 bits and is equivalent to the length of an IPv4 address. Consequently, we conclude that as long as the probability q is greater than or equal to a threshold 0.025, i.e., the network has some randomicity, V is less than the 32-bit length of an IPv4 address in the typical network configuration.

We now try to increase the value of N in the case of q=0.025 and K=10. The parameters L and V have been re-calculated. The calculation results are shown in Fig. 5. L and V increase with N in the typical network configuration. When N reaches 2^{56}, V is close to the 32-bit length of an IPv4 address.

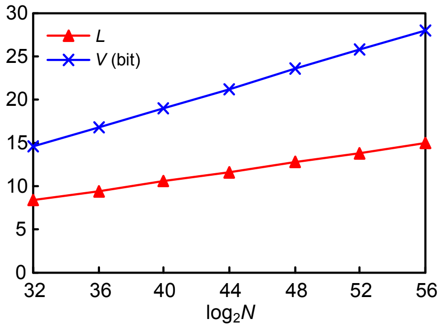

Fig. 5 Variation in V and L in relation to N in the WS small-world model

6.2.3 BA scale-free model

The construction algorithm of a BA scale-free network is as follows. Initially, there exists a network with the number of vertexes being m_0. At every step a new vertex is introduced and is connected to m existing vertexes with $m \le m_0$. The probability of the new vertex being connected with the existing vertex i is denoted as Π_i, which satisfies

$$\Pi_i = \frac{k_i}{\sum_j k_j}, \tag{11}$$

where j is an arbitrary vertex in the network, and k_i and k_j are the degrees of vertexes i and j, respectively. Repeating the above step t times, a network with $N=t+m_0$ vertexes can be constructed.

The average path length of a BA scale-free network can be calculated using the following equation (Cohen and Havlin, 2003):

$$L \approx \frac{\ln N}{\ln \ln N}. \tag{12}$$

The distribution function of the degrees of vertexes of the BA scale-free network is (Dorogovtsev *et al.*, 2000)

$$P(k) = \frac{2m(m+1)}{k(k+1)(k+2)} \approx 2m^2 k^{-3}. \tag{13}$$

Consequently, the average degree of vertexes can be deduced as follows:

$$K = \sum_{k=1}^{\infty} kP(k) \approx 2m. \tag{14}$$

The value of N is set to be 2^{32}. The value of m is set to 1, 2, 3, and so on. According to Eqs. (14), (12), (4), and (5), the parameters K, L, and V can be calculated. The calculation results are shown in Fig. 6.

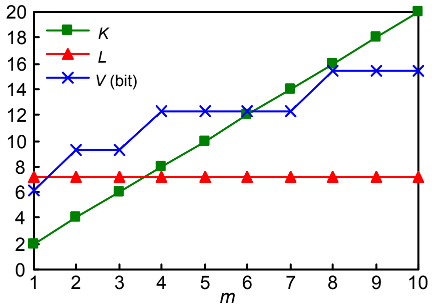

Fig. 6 Variation in V, K, and L in relation to m in the BA scale-free model

K increases linearly with parameter m. L is not related to parameter m. Moreover, V increases with parameter m, but the rate of increase is very small. In the typical network configuration with K being kept between 6 and 14, V varies between 9 and 13 bits, far less than the 32-bit length of an IPv4 address.

We now try to increase the value of N in the case of K=10. The parameters L and V have been re-calculated. The calculation results are shown in Fig. 7. L and V increase with N in the typical network configuration. When N reaches 2^{105}, V is close to the 32-bit length of an IPv4 address.

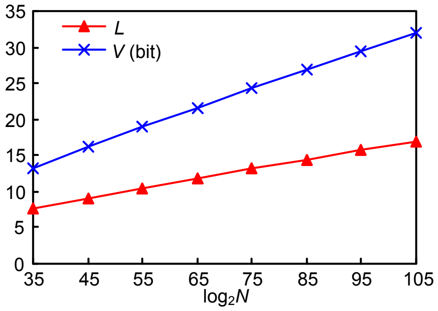

Fig. 7 Variation in V and L in relation to N in the BA scale-free model

7 Simulation experiments

To validate the analytical results in a practical network topology environment, simulation experiments were carried out. In the simulations, the topology generator named BRITE (Boston University representative Internet topology generator) (Medina *et al.*, 2001) was introduced to generate network topologies with a designated number of routers. The VNs were constructed based on the generated network topologies. The programs were written to implement vector switching and count the average length of the VAs in the simulated VNs.

We made use of BRITE software to generate a series of network topologies with different numbers of routers, constructed the simulated VNs on the basis of these topologies, and counted the average length of the VAs. The simulation results are shown in Fig. 8.

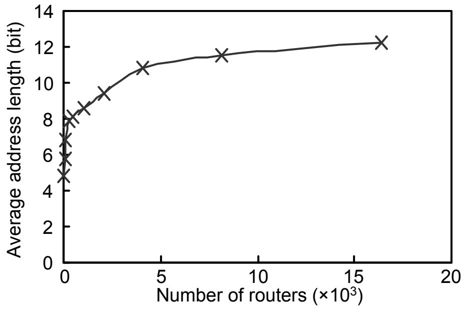

Fig. 8 Variation in *V* in relation to the use of different numbers of routers

The average length of the VAs *V* increases with the number of routers or the network scale. When the number of routers reaches 10 000, which corresponds to a middle or large scale communication network and can accommodate the millions to hundreds of millions of hosts, *V* is about 12 bits, which is far less than the 32-bit length of an IPv4 address. In the network with 10 000 routers, the distribution of the length of the VAs is close to normal (Fig. 9). Most address length values are distributed around the average length of 12. The emergence probability of an address with 9- to 14-bit length is up to more than 90%.

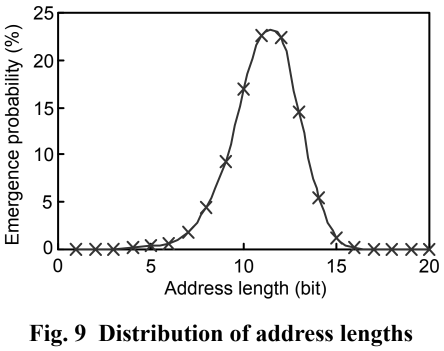

Fig. 9 Distribution of address lengths

8 Conclusions

From the above theoretical analysis and the results of simulation experiments, the following conclusions can be deduced. When the VAs are used to construct a global network, the average length is far less than the 32-bit length of an IPv4 address when the same number of users are accommodated. In other words, a VN with a 32-bit average length address can accommodate many more users than an IPv4 network. This conclusion is independent of the topology of practical communication networks. This research provides the theoretical evidence for the VA to be applied in practical communication networks.

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