國 立 交 通 大 學

電信工程學系

碩 士 論 文

A Reliable Routing Algorithm for Mobile Ad-Hoc Networks

對於移動式隨建即連網路的一種可靠路由方法

研究生：趙偉臣

指導教授：李程輝　博士

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對於隨建即連網路的一種安全路由方法

研究生： 趙偉臣　　　　　　　　指導教授： 李程輝 教授

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中文摘要

隨建即連的網路是由一群行動主機自我組織起來的網路，和傳統的移動無線網路不同的地方在於隨建即連的網路不需要依靠一些固定的基礎設施，例如基地台(Base station)以及接取點(Access point)，他們的通訊方式是藉由中間節點的轉送，以多點跳躍(multi-hop)的方式來完成，由於不受那些基礎設施的限制，所以移動性高，而且部署非常容易。由於這些主機會一直移動，造成整個網路的拓樸不斷的改變，所以必須要有一種快速的方法來偵測目前的拓樸(topology)情況，當使用中的路徑中斷時，才能夠迅速的尋找到另外一條路徑來繼續傳送。在無線網路中，安全性是一個很重要的關鍵，由於在一個無線的環境下傳送資料是非常不可靠的，所以安全性也必須要考慮進去。我們研究了許多種路由的方法以及增加安全性的方法，由於我們的目標是希望整個方法是能夠迅速以及簡單，所以我們提出了一個方法，使得尋找路徑加上增加安全性能夠用一個簡單的方法來實現。

A Reliable Routing Algorithm for Mobile Ad-Hoc Networks

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Abstract

An ad hoc network is a network composed by a group of mobile hosts. Unlike traditional mobile wireless networks, ad hoc networks do not rely on any fixed infrastructure such as base stations and access points. These mobile hosts complete their transmission by transferring the data by intermediate nodes and send the data by multi-hop. Because ad hoc networks do not limit to the infrastructure, they have high mobility and they can be built easily. Because these hosts move, the topology of the network will always change. We have to use an algorithm to detect the topology fast. When some links are broken, we can find another path to keep transmitting the data as fast as possible. In wireless networks, security is a very important issue. Data transmission is vulnerable in the wireless surrounding, so we have to consider the security. There are many proposed routing methods and many ways to enhance the security. Because our goal is how to find another route to keep transmission when some links are broken and enhance the security easily, our proposed algorithm which combines the redundancy base multi-path routing protocol and the Diffie-Hellman key exchange algorithm can achieve our goal.

誌　　謝

特別感謝我的指導教授—李程輝教授，在這碩士班的兩年之中所給予我的指導、鼓勵以及協助，提供許多寶貴的意見，使得碩士班的兩年生活感到非常充實，而且才能讓我能夠順利的完成這個論文，在此，向我的指導教授致上最深的感謝。

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感謝我的父親趙榮宗先生以及母親莊桑銀小姐，從小到大對我的教育以及栽培，無私的付出，才能讓我無後顧之憂完成論文。

僅以本論文獻給我愛的家人以及朋友。

2005.6 新竹交大

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Chapter 1

Introduction

1.1 Background

As wireless network nodes proliferate and as applications using the Internet become familiar to a wider class of customers, those customers will expect to use networking applications even in situations where the Internet itself is not available. For example, people using laptop computers at a conference in a hotel might wish to communicate in a variety of ways, without the mediation of routing across the global Internet. Yet today such obvious communications requirements can not be easily met using Internet protocols. The proposals to be described allow mobile computer users with wireless communication devices to set up a possibly short-lived network just for the communication needs of the moment – in other words, an ad hoc network.

Ad hoc networks are a paradigm of wireless communication for mobile hosts (which we call nodes). In an ad hoc network, there is no fixed infrastructure such as base stations or mobile switching centers. Mobile nodes within each other's radio range communicate directly via wireless links, while those that are far apart rely on other nodes to relay messages as routers. Node mobility in an ad hoc network causes frequent changes of network topology. Figure 1.1 shows an example: initially, nodes

A and D have a direct link between them. When D moves out of A’s radio range, the link is broken. However, the network is still connected, because A can reach D through C, E and F.

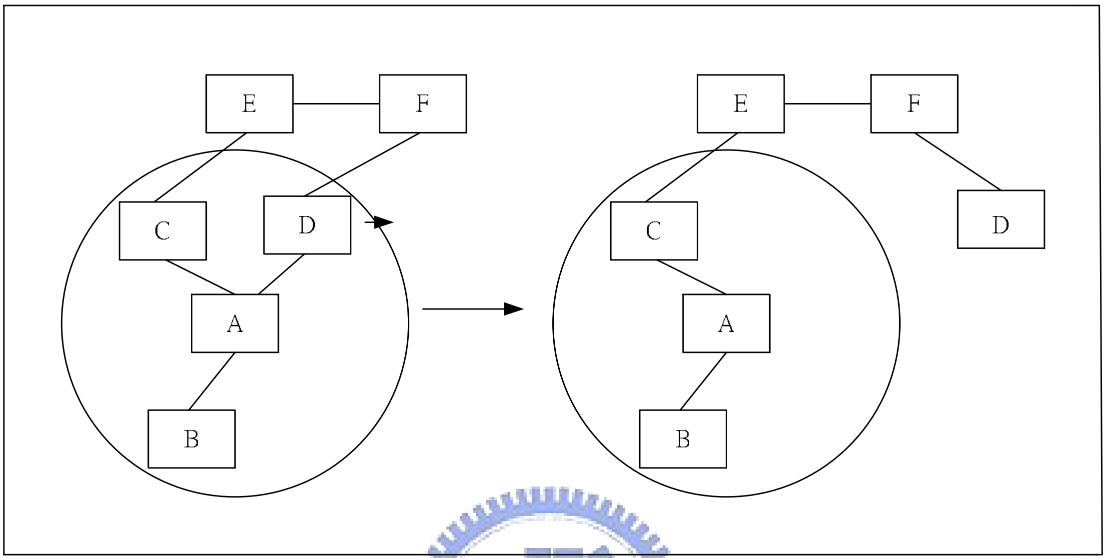


Figure 1.1 Topology changes in ad hoc networks

In ad hoc networks, all the transmission is wireless. The security is an important issue for ad hoc networks, especially for security-sensitive applications. A mobile ad hoc network is a collection of wireless mobile nodes that are capable of communicating with each other without the use of network infrastructure or any centralized administration. One main challenge in the design of this network is its vulnerability to security attacks. Ad hoc network is vulnerable to the same kind of attacks present in the wired network. The attack presents in the wired network can be easily overcome by using security mechanisms such as encryption to provide confidentiality, authentication, digital signature, integrity, non-repudiation etc. However, these services will be effective only when secret keys are shared among nodes. This requires centralize key management and distribution algorithms, which is difficult in an ad hoc network due to its flat infrastructure.

Secure routing and intrusion detection is easier in a wired network because of its steady network topology, which enables static routing and dedicated router. Wired network routers also have more bandwidth and CPU power. So encryption, authentication and digital signature are easily incorporated at every node without power and bandwidth constraints. But in an ad hoc network, each node acts as a router and there is restriction on power consumption. This prevents the usage of complex encryption algorithm.

In the wired network it is easier to establish a trust relationship among the hierarchical infrastructure. In an ad hoc network establishing a trust relationship is quite hard because of its self-organizing nature and mobility. In any wireless network, messages can be eavesdropped without physical access to the network components. Thus securing an ad hoc network is a challenging task.

The security of the data transmission is important and we know that in an ad hoc network key distribution is not easy. So in this thesis, we find a easy way to encrypt the data and ensure that the data will not be eavesdropped.

1.2 Security goals

In [1] Zhou and Hass provide five security goals. To secure ad hoc networks, we have to consider the following attributes: availability, confidentiality, integrity, authentication, and nonrepudiation.

Availability ensures the survivability of network services despite denial-of-service attacks. A denial-of-service attack could be launched at any layer of an ad hoc network. On the physical and media access control layers, an adversary could employ jamming to interfere with communication on physical channels. On the network layer, an adversary could disrupt the routing protocol and disconnect the network.

Confidentiality ensures that certain information is never disclosed to unauthorized entities. Network transmission of sensitive information, such as strategic or tactical military information, requires confidentiality. Leakage of such information to enemies could have devastating consequences. Routing information must also remain confidential in certain cases because the information might be valuable for enemies to identify and locate their targets in a battlefield.

Integrity guarantees that a message being transferred is never corrupted. A message could be corrupted because of transmission failures, such as radio propagation impairment, or because of malicious attacks on the network.

Authentication enables a node to ensure the identity of the peer node with which it is communicating. Without authentication, an adversary could masquerade as a node, thus gaining unauthorized access to resource and sensitive information and interfering with the operation of other nodes.

Finally, nonrepudiation ensures that the origin of a message can not deny having sent the message. Nonrepudiation is useful for detection and isolation of compromised nodes. When node A receives an erroneous message from node B, nonrepudiation allows A to accuse B using this message and to convince other nodes that B is compromised

1.3 Related work

Attacks in an ad hoc network vary from passive eavesdropping to active denial of service attack. Various researchers have focused on handling one or more of these issues. Zhou and Hass [1] have used threshold cryptography to provide secure routing and to establish secure key management service. However, a dealer should be present to issue the global secret key. This increases the complexity and vulnerability.

Marti [2] has used a different approach wherein extra facilities are installed in the network to detect and mitigate routing misbehavior with the help of watchdogs and path raters. Packets being forwarded by the intermediate node will be stored in its buffer. With the help of this, the intermediate node monitors whether the downstream node forwards the packet without any modification. This consumes more memory and increases the computation demands at the intermediate node. Further, if the intermediate node moves due to mobility, then there will be no watchdog to monitor forwarding or modification of packets.

Dahill [3] has proposed authenticated routing for ad hoc networks where it requires a trusted certification authority. Every node that forwards a route request or a route reply must also sign it. This process increases the computation and routing overhead.

Papadimitrators and Hass [4] have proposed a secure routing protocol (SRP). This provides secure routing but relies on network geometry, which is not suitable for an ad hoc network. In SRP, there is a pre-association of a secret key between the source and destination nodes, which is applied for transmitting the routing packets.

Perlman studies how to protect routing information from compromised routers in the context of Byzantine robustness [5]. The study analyzes the theoretical feasibility of maintaining network connectivity under such assumptions. Kumar recognizes the problem of compromised routers as a hard problem, but provides no solution [6]. Other works [7,8,9] give only partial solutions. The basic idea underlying these solutions is to detect inconsistency using redundant information and to isolate compromised routers.

1.3 Organization of the Thesis

The rest of this thesis is organized as follows. In Chapter 2, we will see some routing protocol for ad hoc networks. Chapter 3 will introduce some security mechanisms. Our proposed approach will be in Chapter 4. Finally we will give a conclusion in Chapter 5.

Chapter 2

Some routing protocols for ad hoc networks

There are many routing protocols in mobile ad hoc networks (MANETs). These protocols mainly can be classified into three categories: Proactive (table driven) routing protocols, Reactive (on-demand) routing protocols, and Hybrid routing protocols.

2.1 Proactive (table-driven) routing protocols

In proactive (table-driven) routing protocols the mobile hosts (MHs) update and exchange routing information (routing tables) with their neighbors periodically or whenever the network topology has changed. Therefore, every MH can know the topology of the whole network. Once a host wants to communicate with the other host, it looks up the entry of the routing table and sends the data to the next hop immediately. In table driven routing protocols, every host have to maintain one or more routing table to keep the information of the topology of the network. Hence, the exhaustion of resource in proactive routing protocols is higher than other routing protocols.

DSDV (Destination-Sequenced Distance-Vector) [10] routing protocol is a table-driven algorithm. DSDV extends the basic Bellman-Ford mechanism by attaching a sequence number that is originated by the destination to each distance.

This destination sequence number is used to determine the "freshness" of a route. Every node in the MANETs maintain a routing table containing the distances from itself to possible destinations. Figure 2.1 shows that each mobile host exchanges the routing table periodically by means of broadcasting even though the node does not want to transmit data.

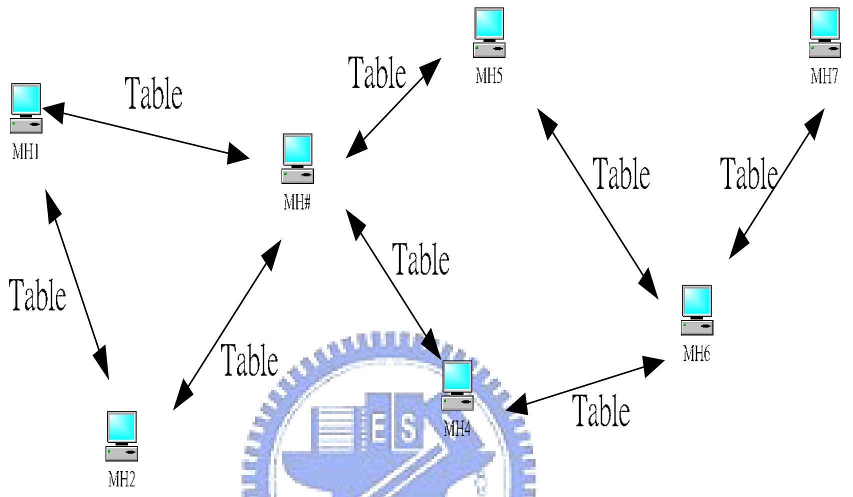


Figure 2.1 DSDV (Destination-Sequenced Distance-Vector)

The entry in the routing table contains the address of the destination node, the address of the next hop, a sequence number and the metric (the number of hops required to reach the destination node). The sequence number is tagged by the destination node and it can make loop free and keep the freshness of the routing information. Routes with more recent sequence numbers are preferred for making packet forwarding decisions by a host. For routes with the equal sequence number, the one with the smallest distance metric is chosen. Each time a host sends an update to its neighbors, its current sequence number is incremented and included in the update. The metric (hop count) field will be set ∞ when the node detects a broken link to the next hop and broadcasts the information. Any node that receive the information with

∞ hop count and have an equal or later sequence number with a finite hop count value will disseminate the unreachable information about that destination node. Figure 2.2 shows the example of DSDV topology movement and Table 2.1 shows the routing table of MH4 before the movement of MH1 and Table 2.2 shows the updated routing table of MH4 after the movement.

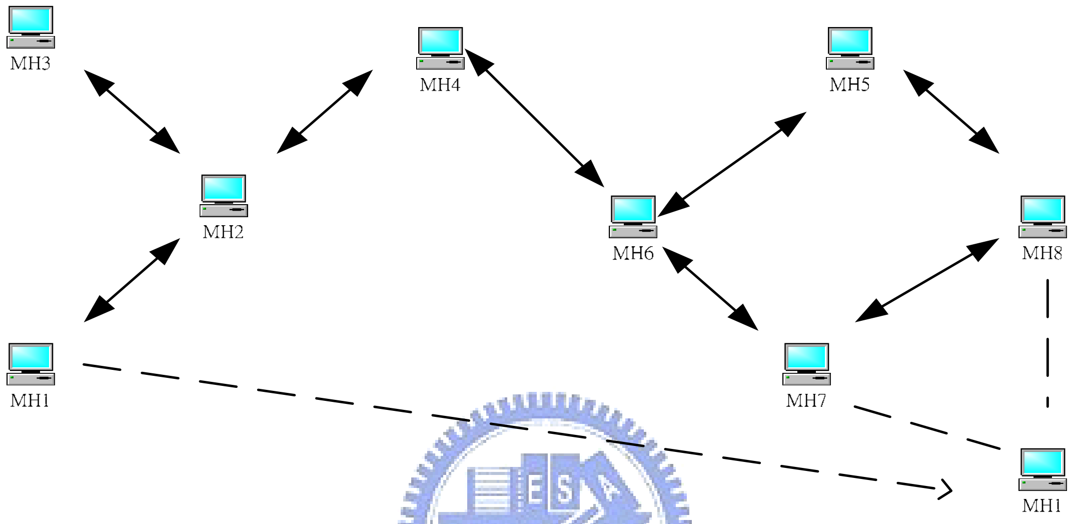


Figure 2.2 The movement of MH1

Destination	Metric	Sequence Number
MH1	2	S406_MH1
MH2	1	S128_MH2
MH3	2	S564_MH3
MH4	0	S710_ MH4
MH5	2	S392_MH5
MH6	1	S076_MH6
MH7	2	S128_MH7
MH8	3	S050_MH8

Table 2.1 MH4 advertised routing table

Destination	Metric	Sequence Number
MH4	0	S820_MH1
MH1	3	S516_MH2
MH2	1	S238_MH3
MH3	2	S674_ MH4
MH5	2	S502_MH5
MH6	1	S186_MH6
MH7	2	S238_MH7
MH8	3	S160_MH8

Table 2.2 MH4 advertised routing table (Updated)

2.2 Reactive (on-demand) routing protocol

In reactive (on-demand) routing protocol [11, 12, 13, 14], a source node finds the new route to transmit data by sending the RREQ (Route Request) packet. When the destination receives the RREQ packet, it will reply a RREP (Route Reply) packet to the source node. After receiving the RREP packet, source node begin to communicate with the destination node. Therefore, MHs do not have to exchange their routing table periodically when they do not want to communicate with the other node even if the MHs have moved. In this way, there are no extra overheads when the topology has changed.

2.2.1 DSR (Dynamic Source Routing)

DSR [15] is based on the on-demand source routing concept. One of the primary differences between DSR and AODV is the control packets (RREQ, RREP, RERR) that carry the complete path from the source to the destination.

2.2.1.1 Route Discovery

When some node S originates a new packet destined for some node D, it places in the header of the packet a source route giving the sequence of hops that the packet should follow. Normally, S obtains a suitable source route by searching its route cache of routes previously learned, but if no route is found in its cache it initiates the route discovery protocol to find a new route to D dynamically. In this case, we call S the initiator and D the target of the route discovery.

Figure 2.3 illustrates an example route discovery, in which node A is attempting to discover a route to E. To initiate the route discovery, A transmits a RREQ (Route Request) message as a single local broadcast packet, which is received by all nodes currently within wireless transmission range of A. Each RREQ packet identifies the initiator and target of the route discovery and also contains a unique request ID, determined by the initiator of the request. Each RREQ also contains a record listing the address of each intermediate node through which this particular copy of the RREQ message has been forwarded. This route record is initialized to an empty list by the initiator of the route discovery.

When another node receives a RREQ, if it is the target of the route discovery it returns a RREP (Route Reply) message to the route discovery initiator, giving a copy of the accumulated route record from the RREQ; when the initiator receives this RREP, it caches this route in its route cache for use in sending subsequent packets to the destination. Otherwise, if the node receiving the RREQ recently saw another RREQ message from this initiator bearing this same request ID, or if it finds that its own address is already listed in the route record in the RREQ message, it discards the request. If not, this node appends its own address to the route record in the RREQ message and propagates it by transmitting it as a local broadcast packet (with the same request ID).

In returning the RREP to the route discovery initiator, such as node E replying to A in Figure 2.3, node E simply reverse the sequence of hops in the route record.

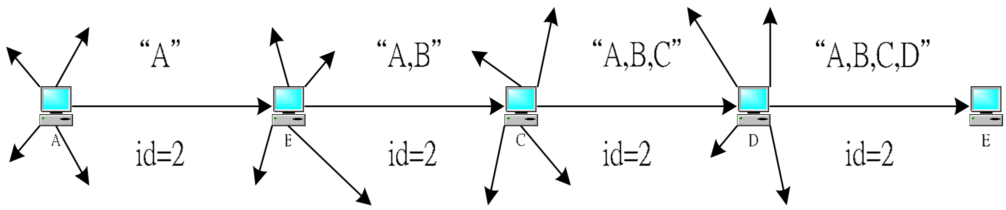


Figure 2.3 Route discovery example with node A as the initiator and node E as the target.

2.2.1.2 Route Maintenance

When originating or forwarding a packet using a source route, each node transmitting the packet is responsible for confirming that the packet has been received by the next hop along the source route; the packet is re-transmitted (up to maximum number of attempts) until this confirmation of receipt is received. For example, in the situation illustrated in Figure 2.4, node A has originated a packet for E using a source route through intermediate nodes B, C, and D. If the packet is retransmitted by some hop the maximum number of times and no receipt confirmation is received, this node returns a RERR (Route Error) message to the original sender of the packet. For example, in Figure 2.4, if C is unable to deliver the packet to the next hop D, C returns a RERR to A, stating that the link from C to D is currently broken. Node A then removes this broken link from its cache, and any retransmission of the original packet is a function for upper-layer protocols such as TCP. For sending such a retransmission or other packets to this same destination E, if A has in its route cache another route to E (for example, from additional RREPs from its earlier route discovery or from having overheard sufficient routing information from other packets), it can send the packet using the new route immediately. Otherwise, it may perform a new route discovery for this target.

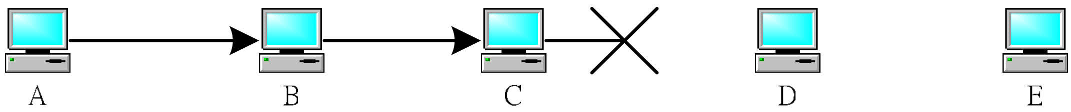


Figure 2.4 Route maintenance example (Node C is unable to forward a packet from A to E over its link to the next hop, D.)

2.2.2 AODV (Ad Hoc On-Demand Distance-Vector) protocol

AODV [15] does not attempt to maintain routes from every node to every other node in the network. Routes are discovered on an as-needed basis and are maintained only as long as they are necessary. Route tables are used by AODV to store pertinent routing information. AODV utilized both a route table.

2.2.2.1 Route Discovery

When a node wishes to send a packet to some destination node, it checks its route table to determine whether it has a current route to that node. If so, it forwards the packet to the appropriate next hop toward the destination. However, if the node does not have a valid route to the destination, it must initiate a route discovery process. To begin such a process, the source node creates a RREQ packet. This packet contains the source node's IP address and current sequence number. The RREQ also contains a broadcast ID, which is incremented each time the source node initiates a RREQ. In this way, the broadcast ID and the IP address of the source node form a unique identifier for the RREQ. After creating the RREQ, the source node broadcasts the packet and then sets a timer to wait for a reply.

When a node receives a RREQ, it first checks whether it has seen it before by noting the source IP address and broadcast ID pair. Each node maintains a record of the source IP address/broadcast ID for each RREQ it receives, for a specified length of time. If it has already seen a RREQ with the same IP address/broadcast ID pair, it silently discards the packet. Otherwise, it records this information and then processes the packet.

To process the RREQ, the node sets up a reverse route entry for the source node in its route table. This reverse route entry contains the source node's IP address and sequence number as well as the number of hops to the source nod and the IP address of the neighbor from which the RREQ was received. In this way, the node knows how to forward a RREP to the source if one is received later. Figure 2.5 indicates the propagation of RREQs across the network as well as the formation of the reverse route entries at each of the network nodes. Associated with the reverse route entry is a lifetime. If this route entry is not used within the specified lifetime, the route information is deleted to prevent stale routing information from lingering in the route table.

To respond to the RREQ, the node must have an unexpired entry for the destination in its route table. Furthermore, the sequence number associated with that destination must be at least as great as that indicated in the RREQ. This prevents the formation of routing loops by ensuring that the route returned is never old enough to point to a previous intermediate node. Otherwise, the previous node would have responded to the RREQ. If the node is able to satisfy these two requirements, it responds by unicasting a RREP back to the source. If it is unable to satisfy the RREQ, it increments the RREQ's hop count and then broadcasts the packet to its neighbors. Naturally, the destination node is always able to respond to the RREQ.

If the RREQ is lost, the source node is allowed to retry the broadcast route discovery mechanism. After rreq_retries additional attempts, it is required to notify the application that the destination is unreachable.

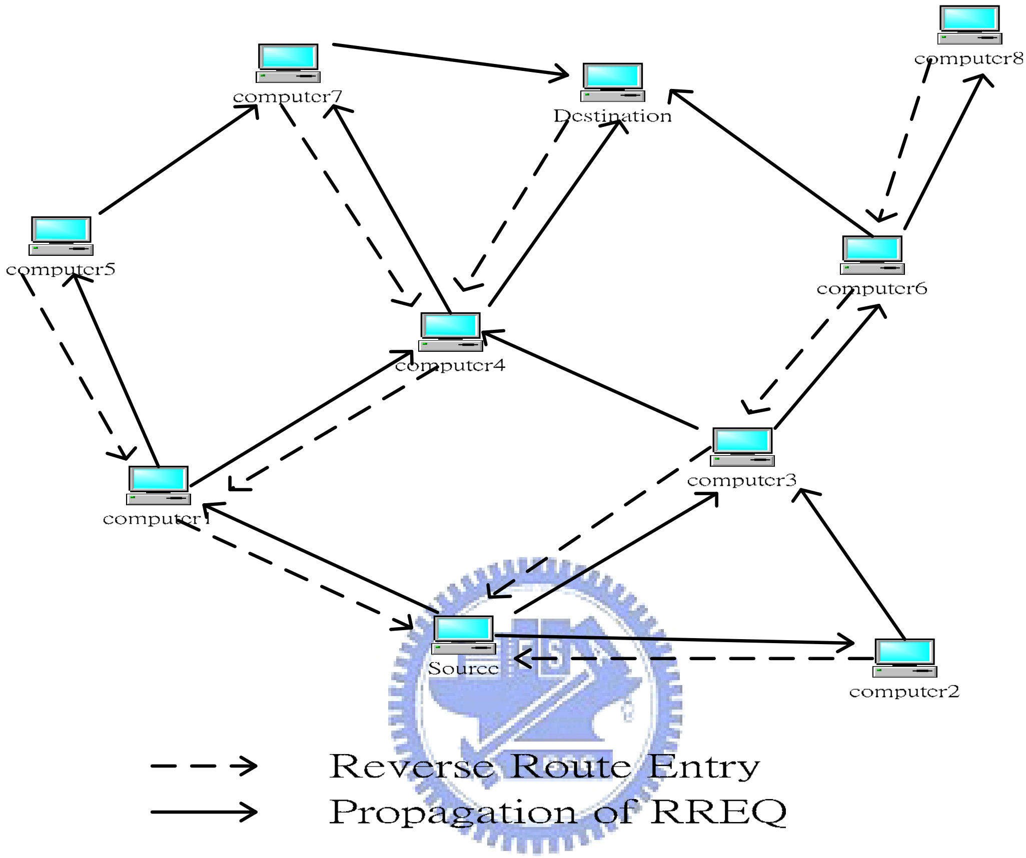


Figure 2.5 Propagation of RREQ throughout the network

2.2.2.2 Forward Path Setup

When a node determines that it has a route current enough to respond to the RREQ, it creates a RREP. For the purposes of replying to a RREQ, any route with a sequence number not smaller than that indicated in the RREQ is deemed current enough. The RREP sent in response to the RREQ contains the IP address of both the source and destination. If the destination node is responding, it places its current sequence number in the packet, initializes the hop count to zero, and places the length of time this route is valid in the RREP's lifetime field. However, if an intermediate node is responding, it places its record of the destination's sequence number in the packet, sets the hop count equal to its distance from the destination, and calculates the amount of time for which its route table entry for the destination will still be valid. It then unicasts the RREP toward the source node, using the node from which it received the RREQ as the next hop.

When an intermediate node receives the RREP, it sets up a forward path entry to the destination in its route table. This forward path entry contains the IP address of the destination, the IP address of the neighbor from which the RREP arrived, and the hop count, or distance, to the destination. To obtain its distance to thedestination, the node increments the value in the hop count field by 1. Also associated with this entry is a lifetime, which is set to the lifetime contained in the RREP. Each time the route is used, its associated lifetime is updated. If the route is not used within the specified lifetime, it is deleted. After processing the RREP, the node forwards it toward the source. Figure 2.6 indicates the path of a RREP from the destination to the source node.

It is likely that a node will receive a RREP for a given destination from more than one neighbor. In this case, it forwards the first RREP it receives and forwards a later RREP only if that RREP contains a greater destination sequence number or a smaller hop count. Otherwise, the node discards the packet. This decreases the number of RREPs propagating toward the source while ensuring the most up-to-date and quickest routing information. The source node can begin data transmission as soon as the first RREP is received and can later update its routing information if it discovers a better route.

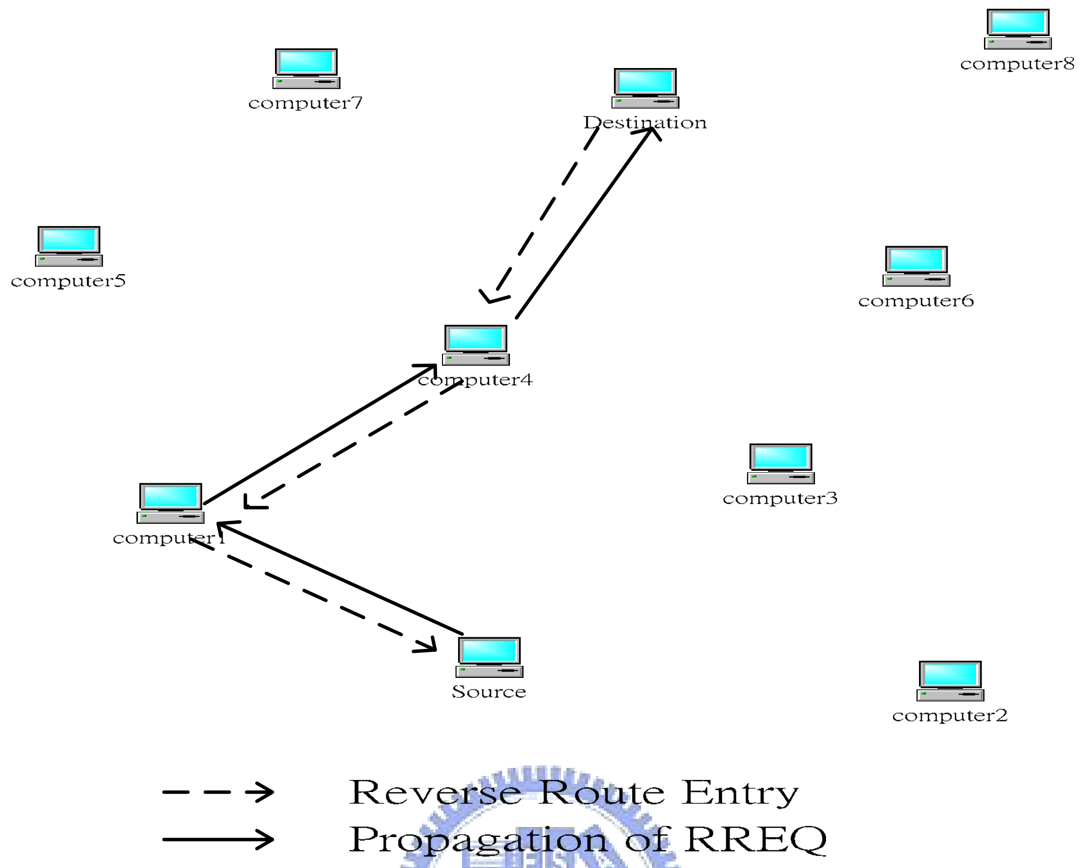
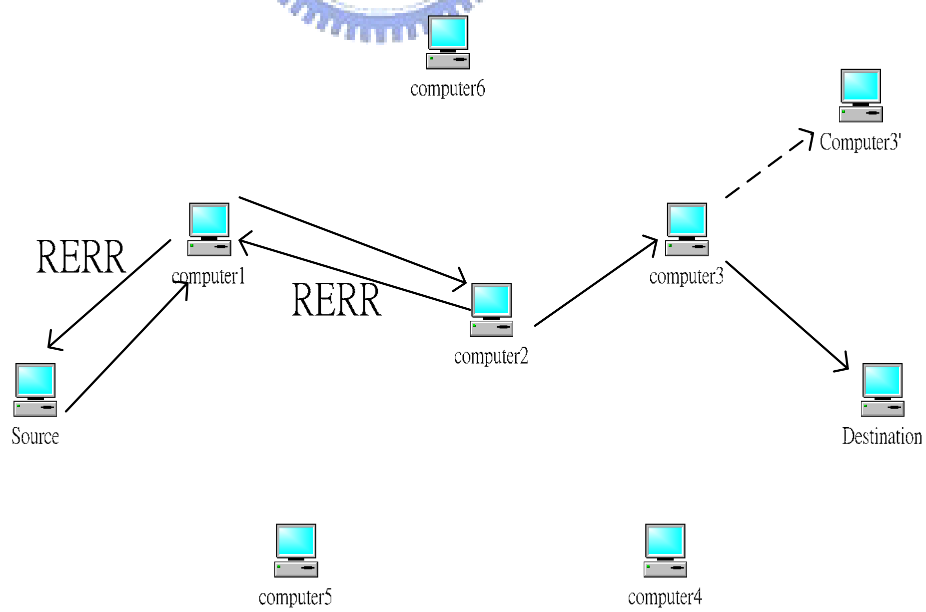


Figure 2.6 Route determination from source to destination

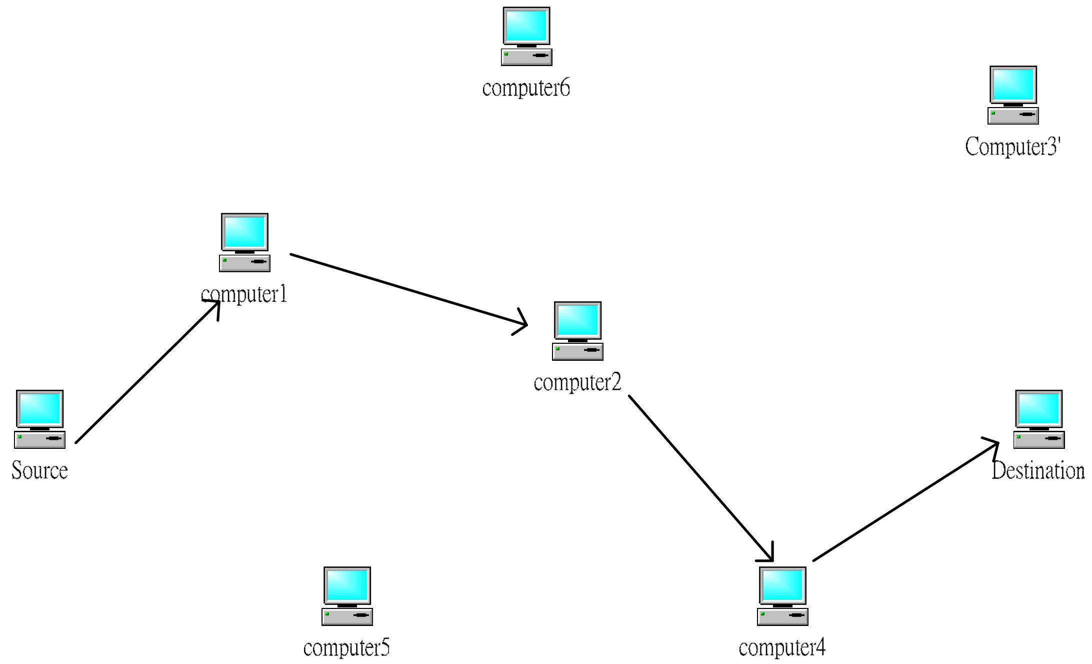
2.2.2.3 Route Maintenance

Once a route has been discovered for a given source/destination pair, it is maintained as long as needed by the source node. Movement of nodes within the ad hoc networks affects only the routes containing those nodes; such a path is called an active path. If the source node moves during an active session, it can reinitiate route discovery to establish a new route to the destination. When either the destination or some intermediate node moves, however, a RERR message is sent to the affected source node. This RERR is initiated by the node upstream (i.e., closer to the source nodes) of the break. It lists each of the destinations that are now unreachable because of the loss of the link. If the node upstream of the break has one or more nodes listed as a precursor node for the destination, it broadcasts the RERR to these neighbors. When the neighbors receive the RERR, they mark their route to the destination as invalid by setting the distance to the destination equal to infinity and in turn propagate the RERR to their precursor nodes, if any such nodes are listed for the destinations in their rout tables. When a source node receives the RERR, it can reinitiate route discovery if the route is still needed.

Figure 2.7 illustrates the route maintenance procedure. In Figure 2.7(a), the original path from the source to the destination is through nodes 1, 2, and 3. Node 3 then moves to location 3’, causing a break in connectivity with node 2. Node 2 notices this break and sends a RERR to node 1. Node 1 marks this route as invalid and then forwards the RERR to the source. On receiving the RERR, the source node determines that it still needs the route, and so it reinitiates route discovery. Figure 2.7(b) shows the new route found through node 4.



(a)



(b)

Figure 2.7 Route maintenance

2.2.3 Hybrid Routing Protocol

In order to combine the advantage of reactive routing and proactive routing respectively, hybrid routing protocols such as ZRP maintains local proactive routing and global reactive routing. Interzone route discovery is based on a reactive route request/route reply scheme. By contrast, intrazone routing uses a proactive protocol to maintain up-to-date routing information to all nodes within its routing zone. However, it needs a coordinated mechanism and it is more complexity to implement and design.

Chapter 3

Some security mechanisms

3.1 Key management

Several techniques have been proposed for the distribution of public keys. Virtually all these proposals can be grouped into the following general schemes: public announcement, public-key authority, and public-key certificates.

3.1.1 Public announcement of public keys

The point of public-key encryption is that the public key is public. Thus, if there is some broadly accepted public-key algorithm, such as RSA, any participant can send his public key to any other participant or broadcast the key to the community at large (Figure 3.1).

Although this approach is convenient, it has a major weakness. Anyone can forge such a public announcement. That is, some user could pretend to be user A and send a public key to another participant or broadcast such a public key.

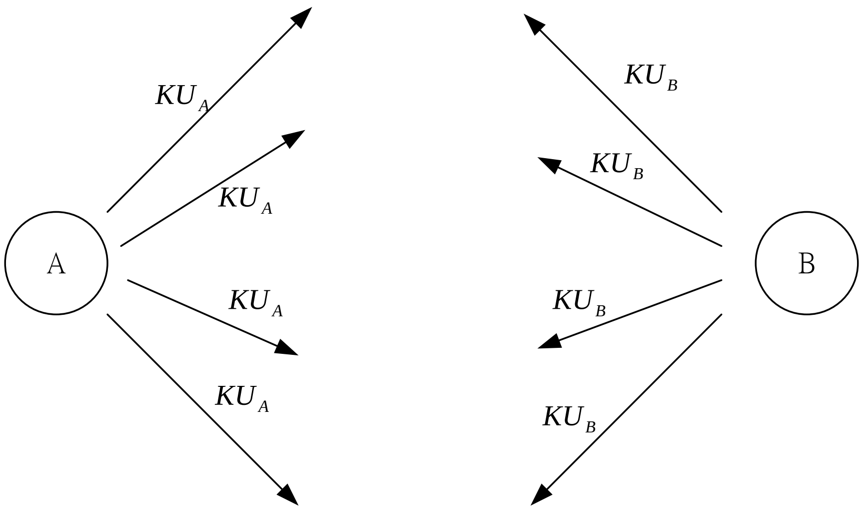


Figure 3.1 Uncontrolled public-key distribution

3.1.2 Public-key authority

Stronger security for public-key distribution can be achieved by providing tighter control over the distribution of public keys from the directory. A typical scenario is illustrated in Figure 3.2. The scenario assumes that a central authority maintains a dynamic directory of public keys of all participants. In addition, each participant reliably knows a public key for the authority, with only the authority knowing the corresponding private key. The following steps (matched by number to Figure 3.2) occur:

1. A sends a timestamped message to the public-key authority containing a request for the current public key of B.
2. The authority responds with a message that is encrypted using the authority's private key, KR_{auth}. Thus, A is able to decrypt the message using the authority's public key. Therefore, A is assured that the message originated with the authority. The message includes the following:
   - B's public key, KU_b, which A can use to encrypt messages destined for B
   - The original request, to enable A to match this response with the

corresponding earlier request and to verify that the original request was not altered before reception by the authority

- The original timestamp, so A can determine that this is not an old message from the authority containing a key other than B's current public key

3. A stores B's public key and also uses it to encrypt a message to B containing an identifier of A (ID_A) and a nonce (N_1), which is used to identify this transaction uniquely.

4,5. B retrieves A's public key from the authority in the same manner as A retrieved B's public key.

At this point, public keys have been securely delivered to A and B, and they may begin their protected exchange. However, two additional steps are desirable:

6. B sends a message to A encrypted with KU_a and containing A's nonce (N_1) as well as a new nonce generated by B (N_2). Because only B could have decrypted message (3), the presence of N_1 in message (6) assures A that the correspondent is B.
7. A returns N_2, encrypted using B's public key, to assure B that its correspondent is A.

3.1.3 Public-key certificates

The scenario of Figure 3.2 has some drawbacks. The public-key authority could be somewhat of a bottleneck in the system, for a user must appeal to the authority for a public key for every other user that it wishes to contact. As before, the directory of names and public keys maintain by the authority is vulnerable to tampering.

An alternative approach is to use certificates that can be used by participants to exchange keys without contacting a public-key authority, in a way that is as reliable as if the keys were obtained directly from a public-key authority. Each certificate contains a public key and other information, is created by a certificate authority, and is given to the participant with the matching private key. A participant conveys its key information to another by transmitting its certificate. Other participants can verify that the certificate was created by the authority. We can place the following requirements on this scheme:

1. Any participant can read a certificate to determine the name and public key of the certificate's owner.
2. Any participant can verify that the certificate originated from the certificate authority and is not counterfeit.
3. Only the certificate authority can create and update certificates.
4. Any participant can verify the currency of the certificate.

A certificate scheme is illustrated in Figure 3.3. Each participant applies to the certificate authority, supplying a public key and requesting a certificate. Application must be in person or by some form of secure authenticated communication. For participant A, the authority provides a certificate of the form $C_A = E_{KR_{auth}}[T, ID_A, KU_a]$, where KR_{auth} is the private key used by the authority. A may then pass this certificate on to any other participant, who reads and verifies the certificate as follows: $D_{KU_{auth}}[C_A] = D_{KU_{auth}}[E_{KR_{auth}}[T, ID_A, KU_a]] = (T, ID_A, KU_a)$.

The recipient uses the authority's public key to decrypt the certificate. Because the certificate is readable only using the authority's public key, this verifies that the certificate came from the certificate authority. The elements ID_A and KU_A provide the recipient with the name and public key of the certificate's holder. The timestamp T validates the currency of the certificate.

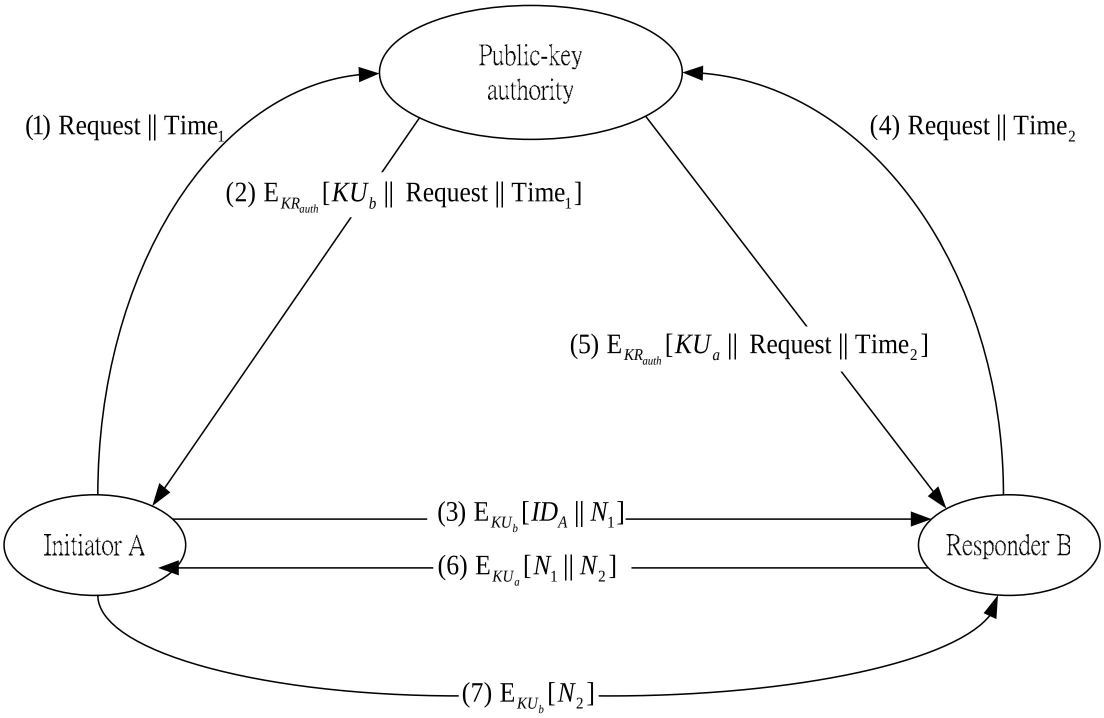


Figure 3.2 Public-key distribution scenario

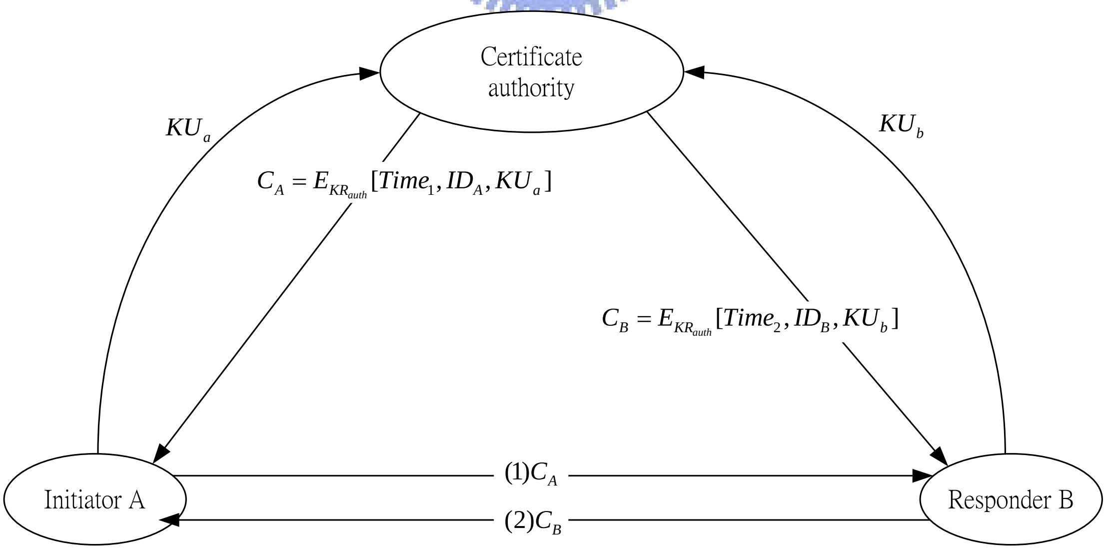


Figure 3.3 Exchange of Public-key certificates

3.2 Diffie-Hellman key exchange

The purpose of the algorithm is to enable two users to exchange a key securely that can then be used for subsequent encryption of message. First, we define a primitive root of a prime number p as one whose powers generate all the integers from 1 to $p-1$. That is, if a is a primitive root of the prime number p, then the numbers $a \bmod p$, $a^2 \bmod p$, $\cdots$, $a^{p-1} \bmod p$ are distinct and consist of the integers from 1 through $p-1$ in some permutation. For any integer b and a primitive root a of prime number p, we can find a unique exponent i such that $b \equiv a^i \bmod p$, where $0 \le i \le (p-1)$. The exponent i is referred to as the discrete logarithm, or index, of b for the base a, mod p. This value is denoted as $\text{ind}_{a,p}(b)$. With this background we can define the Diffie-Hellman key exchange, which is summarized in Figure 3.4.

For this scheme, there are two publicly known numbers: a prime number q and an integer α that is a primitive root of q. Suppose the user A and B wish to exchange a key. User A selects a random integer $X_A < q$ and computes $Y_A = \alpha^{X_A} \bmod q$. Similarly, user B independently selects a random integer $X_B < q$ and computes $Y_B = \alpha^{X_B} \bmod q$. Each side keeps the X value private and makes the Y value available publicly to the other side. User A computes the key as $K = (Y_B)^{X_A} \bmod q$ and user B computes the key as $K = (Y_A)^{X_B} \bmod q$. These two calculations produce identical results:

$$
\begin{aligned}
K &= (Y_B)^{X_A} \bmod q \\
&= (\alpha^{X_B} \bmod q)^{X_A} \bmod q \\
&= (\alpha^{X_B})^{X_A} \bmod q && \text{by the rules of modular arithmetic} \\
&= \alpha^{X_B X_A} \bmod q \\
&= (\alpha^{X_A})^{X_B} \bmod q \\
&= (\alpha^{X_A} \bmod q)^{X_B} \bmod q \\
&= (Y_A)^{X_B} \bmod q
\end{aligned}
$$

The result is that the two sides have exchanged a secret key. Furthermore, because X_A and X_B are private, an opponent only has the following ingredients to work with: q, α, Y_A, Y_B. Thus, the opponent is forced to take a discrete logarithm to determine the key. For example, attacking the secret key of user B, the opponent must compute $X_B = \mathrm{ind}_{\alpha,q}(Y_B)$. The opponent can then calculate the key K in the same manner as user B calculate it.

Global Public Elements

q	Prime number
α	$\alpha < q$ and α a primitive root of q

User A Key Generation

Select private X_A	$X_A < q$
Calculate public Y_A	$Y_A = \alpha^{X_A} \bmod q$

User B Key Generation

Select private X_B	$X_B < q$
Calculate public Y_B	$Y_B = \alpha^{X_B} \bmod q$

Generation of Secret Key by User A

$K = (Y_B)^{X_A} \bmod q$

Generation of Secret Key by User B

$K = (Y_A)^{X_B} \bmod q$

Figure 3.4 The Diffie-Hellman Key Exchange Algorithm

The security of the Diffie-Hellman key exchange lies in the fact that, while it is relatively easy to calculate exponentials modulo a prime, it is very difficult to calculate discrete logarithms. For large primes, the latter task is considered infeasible.

Here is an example. Key exchange is based on the use of the prime number $q = 353$ and a primitive root of 353, in this case $\alpha = 3$. A and B select keys $X_A = 97$ and $X_B = 233$, respectively. Each computes its public key: A computes $Y_A = 3^{97} \bmod 353 = 40$, B computes $Y_B = 3^{233} \bmod 353 = 248$ After they exchange public keys, each can compute the common secret key: A computes $K = (Y_B)^{X_A} \bmod 353 = 248^{97} \bmod 353 = 160$. B computes $K = (Y_A)^{X_B} \bmod 353 = 40^{233} \bmod 353 = 160$.

We assume an attacker would have available the following information: $q = 353; \alpha = 3; Y_A = 40; Y_B = 248$. In this simple example, it would be possibly by brute force to determine the secret key 160. In particular, an attacker E can determine the common key by discovering a solution to the equation $3^a \bmod 353 = 40$ or the equation $3^b \bmod 353 = 248$. The brute force approach is to calculate powers of 3 modulo 353, stopping when the result equals either 40 or 248. The desired answer is reached with the exponent value of 97, which provides $3^{97} \bmod 353 = 40$.

It is important that with larger numbers, the problem becomes impractical.

Figure 3.5 shows a simple protocol that makes use of the Diffe-Hellman calculation.

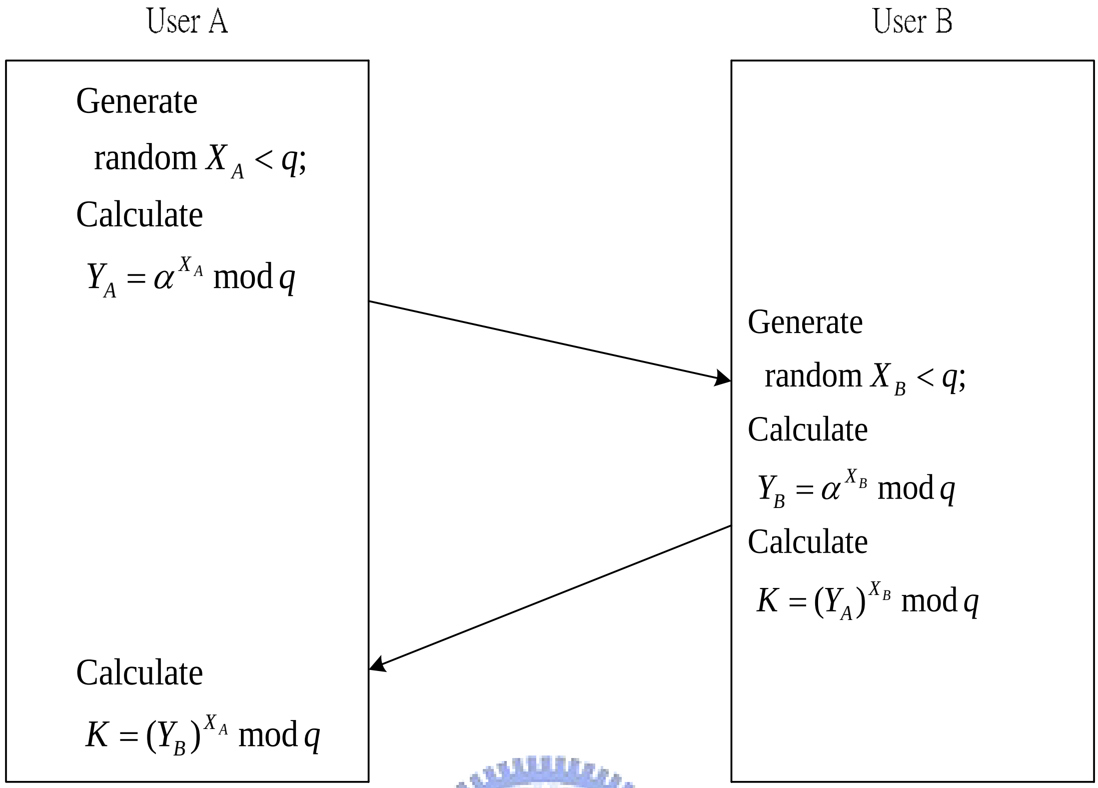


Figure 3.5 Diffie-Hellman Key Exchange

3.3 Summary

The certificate authority mechanism is hard to apply to the mobile ad hoc networks. Each node always moves and will leave the network at any time. If we choose one node to be the certificate authority, it may leave at next second. Then, we have to choose another node to be the certificate authority. This will make the control overhead too heavy. So we use the Diffie-Hellman key exchange algorithm in our proposed algorithm.

Chapter 4

Proposed secure routing protocol for mobile ad hoc networks (MANETs)

The main idea proposed in this thesis is the exchange of a secret key securely, without a centralized key distribution mechanism and the idea that can accomplish dynamic and fast route reconfiguration using information about redundant paths maintained at a source node and intermediate nodes on the main route.

4.1 Redundancy Based Multi-path Routing protocol

In dynamic ad hoc networks, route re-discoveries due to route failures may incur heavy control traffic through the network and cause the increase of packet transmission delay. Hence it is quite required to reduce the number of route re-discoveries by maintaining multiple redundant paths, establishing alternate route promptly and localizing the effect of the failures. Redundancy based multi-path routing (RBMR) [16] protocol that provides dynamic and fast route reconfiguration using information about redundant paths maintained at a source and intermediate nodes on initial route.

4.1.1 Path redundancy

RBMR use ‘path redundancy’ as one of route selection criteria. A route’s path redundancy is expressed by the sum of 'redundancy degrees' of intermediate nodes involved in the route. Each node's redundancy degree signifies the number of redundant links that a node has except one incoming link and outgoing link involved in routing. RBMR is based on the idea that a route with large path redundancy will have more possible redundant paths toward the destination even though there can not exist as many redundant paths as the number of neighbor nodes at each intermediate node. A route with more redundant paths will have the improved reach-ability to the destination in case of route failures. If several possible routes are found during a route discovery process, the path redundancy is considered as an important factor in selecting the desired route. However, the hop distance of the route selected may be longer than in routing algorithms, such as DSR, which selects the shortest path from source to destination. To prevent a route with a relatively excessive hop distance being selected, RBMR will choose the route that has the largest path redundancy per hop, but is not a certain size longer than the hop distance of the shortest candidate route.

4.1.2 Route establishment

Route establishment with RBMR follows a route setup/route reply cycle like typical on-demand ad hoc routing protocols. In this procedure, main route and redundant routes are established. RBMR's operations are based on the assumptions that wireless links between neighboring nodes are symmetric and that each node is aware of the number of nodes in its neighborhood with the help of a data link layer protocol.

4.1.3 Route setup process

A node initiates route establishment procedure by broadcasting a route setup message, Route Setup (RS) packet. An RS packet is flooded throughout the network as shown in Figure 4.1 and carries the information about hop distance and redundancy degree of nodes that it goes through. Any node that receives an RS packet does the following: If the node has already received the RS packet with the same identification, it records the address of the node from which it received the packet as a redundant upstream node and then drops that packet. The recorded node address will be used to build a redundant path if this node is involved in the selected route. If the node recognizes its own address as the destination, it records the forwarding node address, hop count and path redundancy of the packet. To secure the route with more redundancy, the destination will wait for a certain number of RS packets to reach it after receiving the first RS packet. The destination node can receive several RS packets transmitted along different paths from the source node. An RS packet delivered along the shortest route will early reach the destination node and RS packets representing routes with more redundant links may come to later. The destination node adopts the RS packet that reached it later, but contained larger path redundancy per hop, and sends a Route Reply (RR) packet back to the source node via the node from which it received the RS packet. Otherwise, the node records the address of the neighbor node from which it received the RS packet as the upstream node. The recorded node address will be used to build a route during the route reply process. Then, it adds its own redundancy degree to that of the RS packet and broadcasts the updated packet to its neighbor nodes.

Figure 4.1 illustrates how an RS packet is flooded in the entire network. The number under indicates each node's redundancy degree. The node that has the largest redundancy degree is N6. Its redundancy degree is four. Namely, N6 has four redundant nodes. Each intermediate node does not propagate duplicate RS packets. One RS packet will be delivered along the path, N1-N2-N4-N8-N11, which is the shortest one in the example network. Its hop distance id four and its redundancy degree is one. The other RS packet is delivered along the path, N1-N3-N6-N12-N13-N11. This path has one more hop distance and five larger route redundancy degree than the previous one. RMBR chooses the second path as a route.

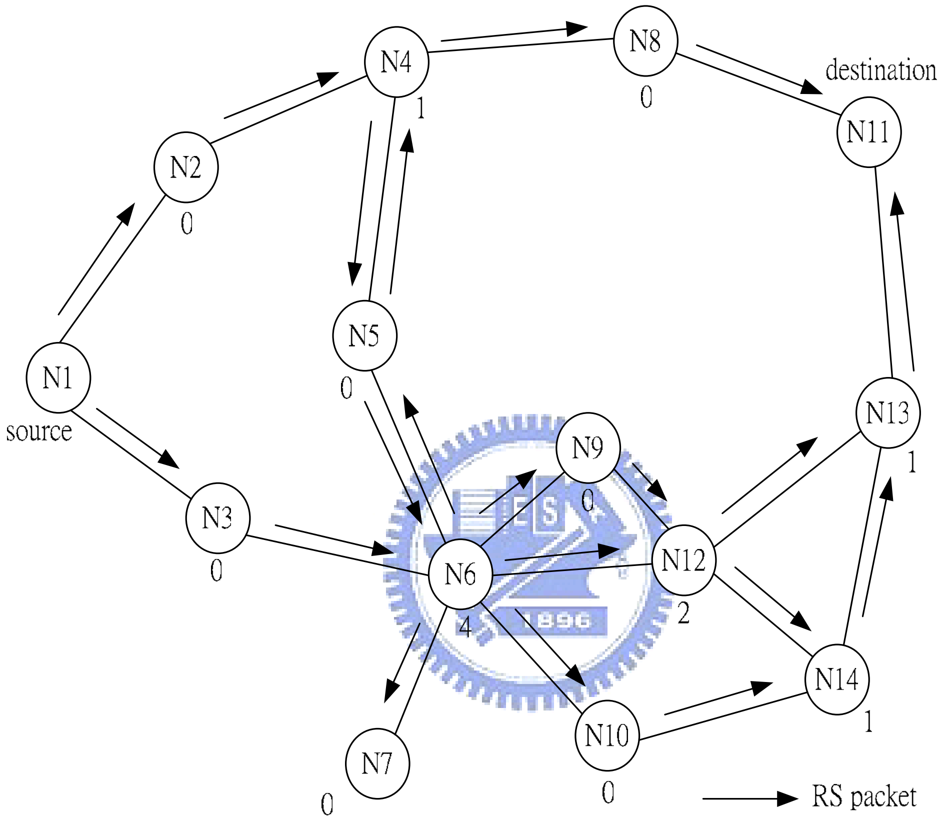


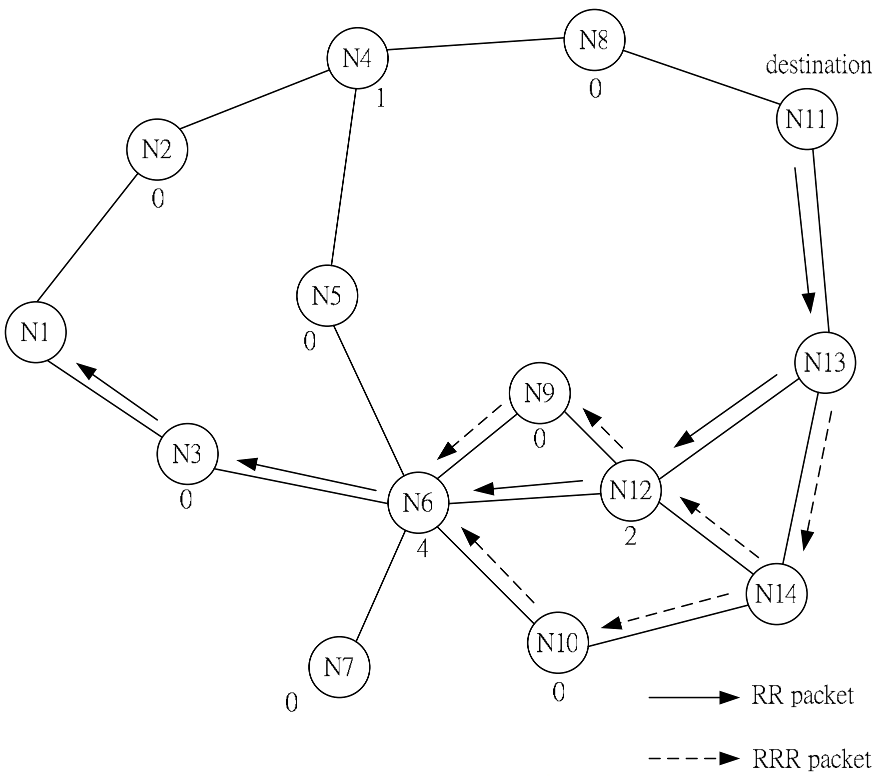
Figure 4.1 The route setup packet flooding

4.1.4 Route reply process

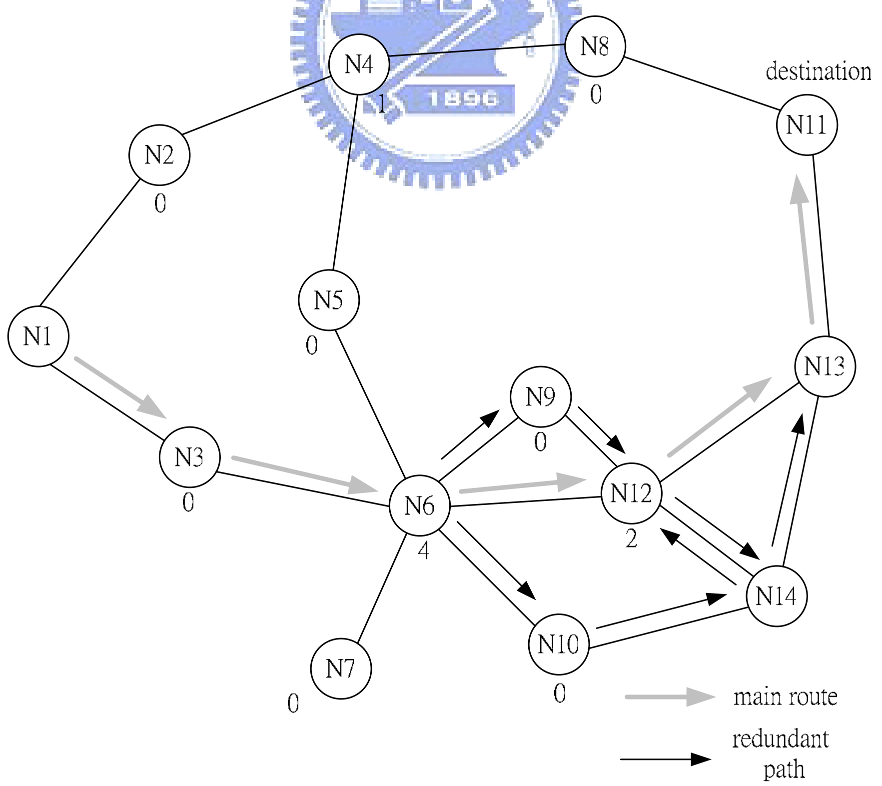
A route containing redundant paths toward the destination is established during the route reply process. The destination node initiates the route reply process by sending an RR packet back to the source node via the node from which it received the corresponding RS packet. An RR packet is forwarded back along the transit nodes the TS packet was traversed. An RR packet carries the hop distance from the destination to the node that received the RR packet. The hop distance is incremented by one whenever the RR packet is forwarded at each intermediate node. Any node that receives an RR packet does the following. If the node recognizes itself as the target node of the received RR packet, it records the forwarding node address of the packet as the next hop for the destination. Then, the node increments the hop distance of the received packet and sends the updated packet to its upstream node, which was recorded during the route setup process. Moreover, if the node has any redundant upstream node recorded, it generates and sends the Redundant Route Reply (RRR) packet to the redundant neighbor nodes. The hop distance of the RR packet is copied into the hop distance field of the RRR packet. If the node recognized its own address as the source, it records the forwarding node address of the RR packet as the next hop for the destination in the route table. Otherwise, the node discards the RR packet.

The RRR packet is used to setup a redundant path of a route. An RRR packet is originated from only nodes along a main route if they have redundant nodes in the upstream direction. RRR packets are forwarded at redundant nodes toward the source node. Any node that receives an RRR packet does the following: If the node exists along the main route, it creates the redundant route table (RRT) entry, which is a set of redundant neighbor nodes for the destination. A redundant next hop field of the RRT entry is filled with the forwarding node address of the RRR packet. If the node is along a redundant path and has already received the RRR packet with the same identification, it discards the packet. This means that a redundant path cannot have any redundant path for itself. Otherwise, it records the forwarding node address of the RRR packet as a redundant next hop for the destination in the RRT entry. Then, it forwards the packet to the upstream nodes.

Figure 4.2 illustrates the route reply process including redundant path setup. When the destination node N11 receives two RS packets from possible routes and as shown in Figure 4.1, it will select a more redundant, but longer route. This route has redundant paths toward N11 at N6 and N12. N6 has two redundant links N6-N9 and N6-N10. To establish a route, N11 sends an RR packet back to the forwarding node N13 of the chosen RS packet. The RR packet is unicast to the source. Nodes receiving the RR packet increment the hop distance by one and then create or update route information for the destination. Once the RR packet reaches the source, the source begins the transmission of data packets. In this example, the data packets are transmitted along the established route N1-N3-N6-N12-N13. As for the redundant route setup, a node receiving an RR packet generates an RRR packet if it has any redundant upstream node. In Figure 4.2 (a), since N13 is along a main route and has a redundant upstream node N14, it generates and sends an RRR packet to N14. If N14 receives the RRR packet, it records redundant path information. The RRR packet is disseminated to other upstream nodes along a main route. In this example network, the RRR packet originating from N13 is delivered to N12 and N6. The two main nodes create the redundant route entry and maintain the redundant path information for N11. N12 has one redundant path N12-N14-N13, and N6 three redundant paths N6-N9-N12 (four hops), N6-N10-N14-N12 (five hops), N6-N10-N14-N13 (four hops). Figure 4.2 (b) shows the route established. In the event of a link failure between N6 and N12, N6 can forward in-transit data packets via one of three redundant paths.



(a) The route reply process



(b) Example of an established route

Figure 4.2 Example of route establishment

4.1.5 Route reconfiguration

4.1.5.1 Failure notification

When a node detected a link failure, but did not have any redundant path for the destination. Route failure information is carried using a Failure Notification (FN) packet and stored in the failure record. Route failure information includes the information about a failure-detecting node, whether the failure-detecting node is along a main route or not, and intermediate transit nodes that an FN packet is propagated through. Any node that receives an FN packet does the following: If the node is along a main route (shortly, main node) and the FN packet is originating from a main node, it records the failure information and finds an alternate redundant path. If the node is a main node and the FN packet is originating from a node along a redundant path (shortly, redundant node), it removes the corresponding redundant path information from the RRT entry. If the node is a main node and the FN packet is originating from a node along an active redundant path (shortly, active redundant node), it records the failure information and finds an alternate redundant path. If the node cannot find a redundant path, it adds its node address to the FN transit node list of the FN packet and propagates the updated packet. Moreover, it deletes all the information about the failure route. If the node is an active redundant node, it deletes the corresponding Routing Table (RT) entry and RRT entry and adds its node address to the FN transit node list of the FN packet and propagates the updated packet. If the node is an inactive redundant node, it deletes the corresponding RRT entry and broadcasts the packet.

4.1.5.2 Finding an alternate path

When a node is along an active main route and recognizes that it cannot forward any more data packets through its outgoing link in use, it begins the procedure to find an alternate path. In the first place, the failure-recognizing node checks if it maintains any redundant path related to the failed route. If the node does not have any redundant path, it tries to finds an alternative redundant path. If a node fails to find a redundant path and is the source node, it initiates a route discovery procedure.

4.1.6 RBMR compare with DSDV and AODV

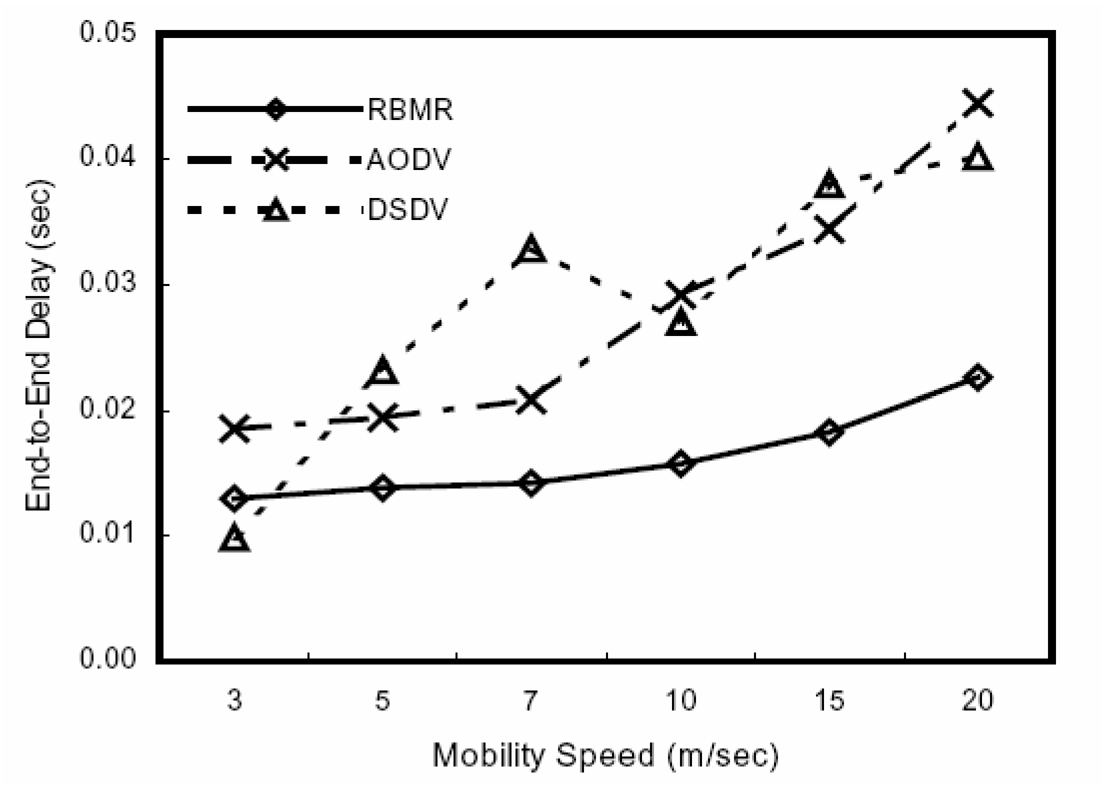


Figure 4.3 End-to-End delay

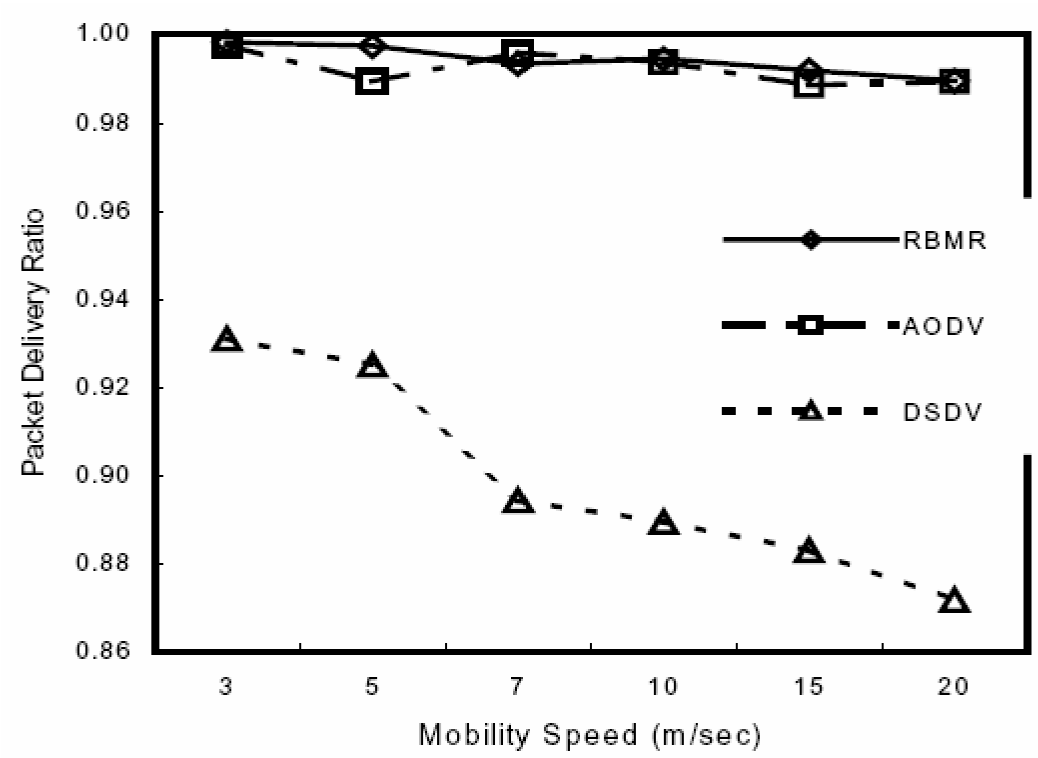


Figure 4.4 Packet delivery ratio

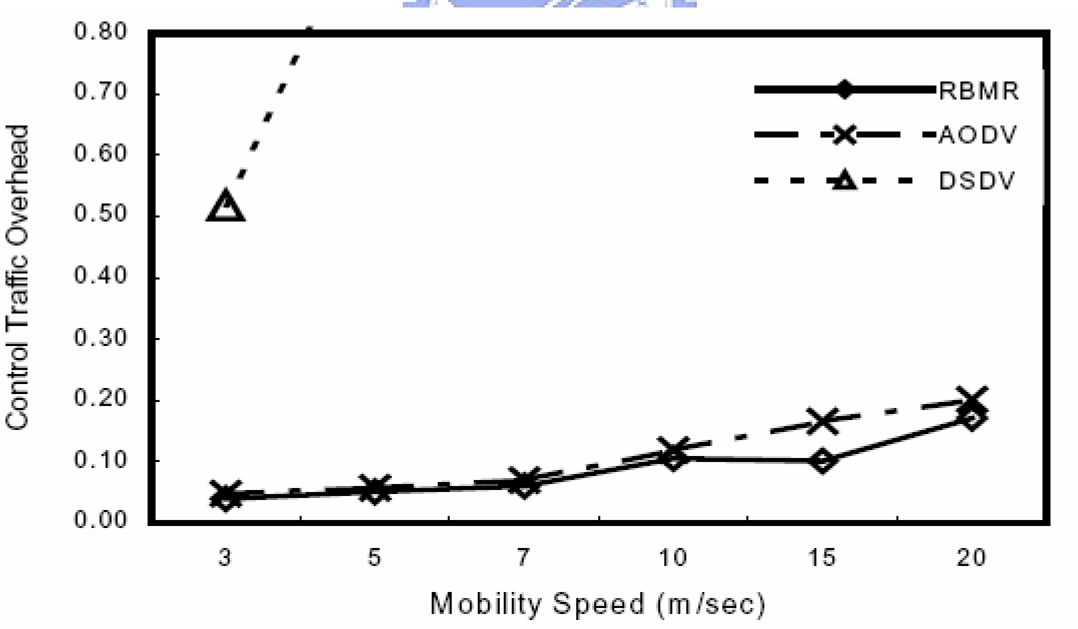


Figure 4.5 Control traffic overhead

4.2 RBMR with Diffie-Hellman key exchange algorithm

The RBMR protocol is first explained, and then the modification to this protocol for RBMR with Diffie-Hellman key exchange algorithm is presented. Before transmitting the data, the node should perform a route discovery process, to determine whether the node is directly reachable within the wireless transmission range or reachable through one or more intermediate network hops through other hosts. When one host sends a packet to another host, the sender may attempt to discover one route using the route setup process. As part of route setup process a route request is broadcast, all the neighbor nodes retransmit this. When it reaches the destination, the destination responds with a route reply message containing the information, to the source. The source sends the data packets using the route.

Our proposed protocol involves the incorporation of the proposed security mechanism in the basic RBMR protocol. The main addition is the handling of the token exchange process prior to key determination. This is incorporated as a part of the route setup process. The source token is generated using the Diffie-Hellman method. It is added to the route request packet to be sent to the destination. The format of the route request packet with the source token is given in table 4.3.

Packet type (RS)
Source address
Destination address
Hop count
Redundancy degree
Source token
Route record
Packet ID

Table 4.1 Route request packet format

As in RBMR, the destination receives a number of route request packets which have traveled through different paths. However, the destination does not send the reply packets as soon as it receives the first request. The destination extracts the source token from all the request packets it receives, and compares them. The value that has been received maximum number of times is taken to be the correct source token. Destination now sends reply packets on the routes having the correct token and an error message is broadcast so that other nodes may get the indication of the particular route that is likely to have a malicious node. The reply packets contain the destination token to be sent to the source. The destination token is derived using the Diffie-Hellman process. The format of the reply packet and error message packet are given in table 4.2 and 4.3.

After retrieving the destination token, the source generates the secret key using the Diffie-Hellman algorithm. The destination also generates the secret key in the same manner. The secret key generated by both the source and the destination will be the same according to Diffie-Hellman method. Using this secret key, data is encrypted using any conventional encryption algorithm. The same secret key can be used for further communication between the two nodes.

Packet type (RR)
Source address
Destination address
Destination token
Route record
Hop count

Table 4.2 Route reply packet format

Packet type (FN)
Detecting node address
Route record

Table 4.3 Error message packet format

In our proposed algorithm, the destination node cannot send the reply packet as soon as it receives the route request. It has to wait until it receives all the route request packets, so that it can compare them and extract the token information. The problem here is that the destination node has no way of determining when all the packets have been received. Hence, practically, it has to wait for a certain threshold number of packets to be received, before it starts the route reply process. Determining the threshold is hard. The threshold value has to be large enough for the success of this algorithm, since a good number of correct tokens have to be received. (Malicious nodes send wrong tokens, and the number of correct tokens should be greater than the number of wrong tokens for the success of our proposed algorithm.). However a large value for the threshold could increase the waiting time before the token-extraction processing at the destination can be done. This could cause a delay in the route discovery process. So, this is a trade-off problem. How many requests should be received is also depend on the density of the network. Thus choosing the threshold value is a difficult task.

Chapter 5

Conclusions

In mobile ad hoc networks, each mobile host will always move and the topology will change all the time. The links between hosts will be broken easily, so it is important to use a routing protocol which can find another route fast when link is broken. Under wireless transmission, To keep the data transmission secure is very important. Our proposed algorithm can achieve both routing reconfiguration fast and data encryption easily. It has less control overhead. This algorithm provide an easy way to make the routing secure.

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