Hop Integrity in Computer Networks [*]

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Abstract

A computer network is said to provide hop integrity iff when any router p in the network receives a message m supposedly from an adjacent router q, then p can check that m was indeed sent by q, was not modified after it was sent, and was not a replay of an old message sent from q to p. In this paper, we describe three protocols that can be added to the routers in a computer network so that the network can provide hop integrity. These three protocols are a secret exchange protocol, a weak integrity protocol, and a strong integrity protocol. All three protocols are stateless, require small overhead, and do not constrain the network protocol in the routers in any way.

Keywords: authentication, Internet, network protocol, router, security, smurf attack, SYN attack, message modification, message replay.

1. Introduction

Most computer networks suffer from the following security problem: in a typical network, an adversary, that has an access to the network, can insert new messages, modify current messages, or replay old messages in the network. In many cases, the inserted, modified, or replayed messages can go undetected for some time until they cause severe damage to the network. More importantly, the physical location in the network where the adversary inserts new messages, modifies current messages, or replays old messages may never be determined.

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Two well-known examples of such attacks in networks that support the Internet Protocol (or IP, for short) and the Transmission Control Protocol (or TCP, for short) are as follows.

i. *Smurf Attack*:

In an IP network, any computer can send a “ping” message to any other computer which replies by sending back a “pong” message to the first computer as required by Internet Control Message Protocol (or ICMP, for short) [Pos81]. The ultimate destination in the pong message is the same as the original source in the ping message. An adversary can utilize these messages to attack a computer d in such a network as follows. First, the adversary inserts into the network a ping message whose original source is computer d and whose ultimate destination is a multicast address for every computer in the network. Second, a copy of the inserted ping message is sent to every computer in the network. Third, every computer in the network replies to its ping message by sending a pong message to computer d. Thus, computer d is flooded by pong messages that it did not requested.

ii.*SYN Attack*:

To establish a TCP connection between two computers c and d, one of the two computers c sends a “SYN” message to the other computer d. When d receives the SYN message, it reserves some of its resources for the expected connection and sends a “SYN-ACK” message to c. When c receives the SYN-ACK message, it replies by sending back an “ACK” message to d. If d receives the ACK message, the connection is fully established and the two computers can start exchanging their data messages over the established connection. On the other hand, if d does not receive the ACK message for a specified time period of T seconds after it has sent the SYN-ACK message, d discards the partially established connection and releases all the resources reserved for that connection. The net effect of this scenario is that computer d has lost some of its resources for T seconds. An adversary can take advantage of such a scenario to attack computer d as follows [CERT96, VVI98]. First, the adversary inserts into the network successive waves of SYN messages whose original sources are different (so that these messages cannot be easily

> detected and filtered out from the network) and whose ultimate destination is d. Second, d receives the SYN messages, reserves its resources for the expected connections, replies by sending SYN-ACK messages, then waits for the corresponding ACK messages which will never arrive. Third, the net effect of each wave of inserted SYN messages is that computer d loses all its resources for T seconds.

In these (and other [Jon95]) types of attacks, an adversary inserts into the network messages with wrong original sources. These messages are accepted by unsuspecting routers and routed toward the computer under attack. To counter these attacks, each router p in the network should route a received m only after it checks that the original source in m is a computer adjacent to p or m is forwarded to p by an adjacent router q. Performing the first check is straightforward, whereas performing the second check requires special protocols between adjacent routers. In this paper, we present a suite of protocols that provide *hop integrity* between adjacent routers: whenever a router p receives a message m from an adjacent router q, p can detect whether m was indeed sent by q or it was modified or replayed by an adversary that operates between p and q.

It is instructive to compare hop integrity with secure routing [Che97, MB96, SMG97], ingress filtering [FS98], and IPsec [KA98a]. In secure routing, for example [Che97], [MB96], and [SMG97], the routing update messages that routers exchange are authenticated. This authentication ensures that every routing update message, that is modified or replayed, is detected and discarded. By contrast, hop integrity ensures that all messages (whether data or routing update messages), that are modified or replayed, are detected and discarded.

Using ingress filtering [FS98], each router on the network boundary checks whether the recorded source in each received message is consistent with where the router received the message from. If the message source is consistent, the router forwards the message as usual. Otherwise, the router discards the message. Thus, ingress filtering detects messages whose recorded sources are modified (to hide the true sources of these messages), provided that these modifications occur at the network boundary. Messages whose recorded sources are modified between adjacent routers in the middle of the network will not be detected by ingress filtering, but will be detected and discarded by hop integrity.

The hop integrity protocol suite in this paper and the IPsec protocol suite presented in [KA98a], [KA98b], [KA98c], [MSS+98], and [Orm98] are both intended to provide security at the IP layer. Nevertheless, these two protocol suites provide different, and somewhat complementary, services. On one hand, the hop integrity protocols are to be executed at all routers in a network, and they provide a minimum level of security for all communications between adjacent routers in that network. On the other hand, the IPsec protocols are to be executed at selected pairs of computers in the network, and they provide sophisticated levels of security for the communications between these selected computer pairs. Clearly, one can envision networks where the hop integrity protocol suite and the IPsec protocol suite are both supported.

Next, we describe the concept of hop integrity in some detail.

2. Hop Integrity Protocols

A *network* consists of computers connected to subnetworks. (Examples of subnetworks are local area networks, telephone lines, and satellite links.) Two computers in a network are called *adjacent* iff both computers are connected to the same subnetwork. Two adjacent computers in a network can *exchange* messages over any common subnetwork to which they are both connected.

The computers in a network are classified into *hosts* and *routers*. For simplicity, we assume that each host in a network is connected to one subnetwork, and each router is connected to two or more subnetworks. A message m is transmitted from a computer s to a faraway computer d in the same network as follows. First, message m is transmitted in one hop from computer s to a router r.1 adjacent to s. Second, message m is transmitted in one hop from router r.1 to router r.2 adjacent to r.1, and so on. Finally, message m is transmitted in one hop from a router r.n that is adjacent to computer d to computer d.

A network is said to provide *hop integrity* iff the following two conditions hold for every pair of adjacent routers p and q in the network.

i. *Detection of Message Modification*:

Whenever router p receives a message m over the subnetwork connecting routers p and q, p can determine correctly whether message m was modified by an adversary after it was sent by q and before it was received by p.

ii. *Detection of Message Replay*:

Whenever router p receives a message m over the subnetwork connecting routers p and q, and determines that message m was not modified, then p can determine correctly whether message m is another copy of a message that is received earlier by p.

For a network to provide hop integrity, two “thin” protocol layers need to be added to the protocol stack in each router in the network. As discussed in [Com88] and [Ste94], the protocol stack of each router (or host) in a network consists of four protocol layers; they are (from bottom to top) the subnetwork layer, the network layer, the transport layer, and the application layer. The two thin layers that need to be added to this protocol stack are the *secret exchange layer* and the *integrity check layer*. The secret exchange layer is added above the network layer (and below the transport layer), and the integrity check layer is placed below the network layer (and above the subnetwork layer).

The function of the secret exchange layer is to allow adjacent routers to periodically generate and exchange (and so share) new secrets. The exchanged secrets are made available to the integrity check layer which uses them to compute and verify the integrity check for every data message transmitted between the adjacent routers.

Figure 1 shows the protocol stacks in two adjacent routers p and q. The secret exchange layer consists of the two processes pe and qe in routers p and q, respectively.

The integrity check layer has two versions: *weak* and *strong*. The weak version consists of the two processes pw and qw in routers p and q, respectively. This version can detect message modification, but not message replay. The strong version of the integrity check layer consists of the two processes ps and qs in routers p and q, respectively. This version can detect both message modification and message replay.

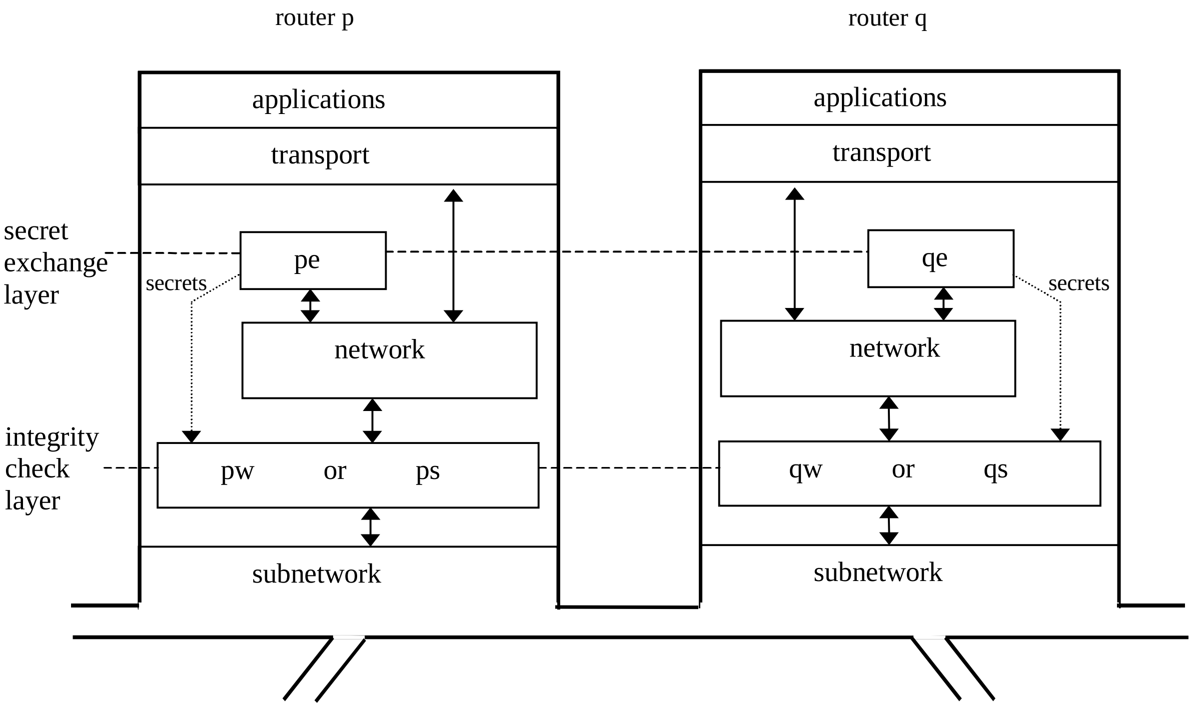


Figure 1. Protocol stack for achieving hop integrity.

Next, we explain how hop integrity, along with ingress filtering, can be used to prevent smurf and SYN attacks (which are described in the Introduction). Recall that in smurf and SYN attacks, an adversary inserts into the network ping and SYN messages with wrong original sources. These forged messages can be inserted either through a boundary router or between two routers in the middle of the network. Ingress filtering (which is usually installed in boundary routers [FS98]) will detect the forged messages if they are inserted through a boundary router because the recorded sources in these messages would be inconsistent with the hosts from which these messages are received. However, ingress filtering may fail in detecting forged messages if these messages are inserted between two routers in the middle of the network. For example, an adversary can log into any host located between two routers p and q, and use this host to insert forged messages toward router p, pretending that these messages are sent by router q. The real source of these messages can not be determined by router p because router p cannot decide whether these messages are sent by router q or by some host between p and q. However, if hop integrity is installed between the two routers p and q, then the (weak or strong) integrity check layer in router p concludes that the forged messages have been modified after being sent by router q (although they are actually inserted by the adversary and not sent by router q), and so it discards them.

Smurf and SYN attacks can also be launched by replaying old messages. For example, the adversary can log into any host located between two routers p and q. When the adversary spots some passing legitimate ping or SYN message being sent from q to p, it keeps a copy of the passing message. At a later time, the adversary can replay these copied messages over and over to launch a smurf or SYN attack. Hop integrity can defeat this attack as follows. If hop integrity is installed between the two routers p and q, then the strong integrity check layer in router p can detect the replayed messages and discard them.

In the next three sections, we describe in some detail the protocols in the secret exchange layer and in the two versions of the integrity check layer. The first protocol between processes pe and qe is discussed in Section 3. The second protocol between processes pw and qw is discussed in Section 4. The third protocol between processes ps and qs is discussed in Section 5.

These three protocols are described using a variation of the Abstract Protocol Notation presented in [Gou98]. In this notation, each process in a protocol is defined by a set of inputs, a set of variables, and a set of actions. For example, in a protocol consisting of processes px and qx, process px can be defined as follows.

```
process  px
inp   <name of input>      :      <type of input>
      …
```

```
          <name of input>      :    <type of input>
    var   <name of variable>   :    <type of variable>
          …
          <name of variable>   :    <type of variable>
    begin
          <action>
    []    <action>
    …
    []    <action>
    end
```

Comments can be added anywhere in a process definition; each comment is placed between the two brackets { and }.

The inputs of process px can be read but not updated by the actions of process px. Thus, the value of each input of px is either fixed or is updated by another process outside the protocol consisting of px and qx. The variables of process px can be read and updated by the actions of process px. Each <action> of process px is of the form:

```
    <guard>   →   <statement>
```

The <guard> of an action of px is either a <boolean expression> or a <receive> statement of the form:

```
    rcv <message> from qx
```

The <statement> of an action of px is a sequence of skip, <assignment>, <send>, or <selection> statements. An <assignment> statement is of the form:

```
    <variable of px> := <expression>
```

A <send> statement is of the form:

```
    send <message> to qx
```

A <selection> statement is of the form:

```
    if <boolean expression>    →   <statement>
    …
    [] <boolean expression>    →   <statement>
    fi
```

Executing an action consists of executing the statement of this action. Executing the actions (of different processes) in a protocol proceeds according to the following three rules. First, an action is executed only when its guard is true. Second, the actions in a protocol are executed one at a time. Third, an action whose guard is continuously true is eventually executed.

Executing an action of process px can cause a message to be sent to process qx. There are two channels between the two processes: one is from px to qx, and the other is from qx to px. Each sent message from px to qx remains in the channel from px to qx until it is eventually received by process qx or is lost. Messages that reside simultaneously in a channel form a sequence <m.1; m.2; …; m.n> in accordance with the order in which they have been sent. The head message in the sequence, m.1, is the earliest sent, and the tail message in the sequence, m.n, is the latest sent. The messages are to be received in the same order in which they were sent.

We assume that an adversary exists between processes px and qx, and that this adversary can perform the following three types of actions to disrupt the communications between px and qx. First, the adversary can perform a *message loss* action where it discards the head message from one of the two channels between px and qx. Second, the adversary can perform a *message modification* action where it arbitrarily modifies the contents of the head message in one of the two channels between px and qx. Third, the adversary can perform a *message replay* action where it replaces the head message in one of the two channels by a message that was sent previously. For simplicity, we assume that each head message in one of the two channels between px and qx is affected by at most one adversary action.

3. The Secret Exchange Protocol

In the secret exchange protocol, the two processes pe and qe maintain two shared secrets sp and sq. Secret sp is used by router p to compute the integrity check for each data message sent by p to router q, and it is also used by router q to verify the integrity check for each data message received by q from router p. Similarly, secret sq is used by q to compute the integrity checks for data messages sent to p, and it is used by p to verify the integrity checks for data messages received from q.

As part of maintaining the two secrets sp and sq, processes pe and qe need to change these secrets periodically, say every te hours, for some chosen value te. Process pe is to initiate the change of secret sq, and process qe is to initiate the change of secret sp. Processes pe and qe each has a public key and a private key that they use to encrypt and decrypt the messages that carry the new secrets between pe and qe. A public key is known to all processes (in the same layer), whereas a private key is known only to its owner process. The public and private keys of process pe are named B_p and R_p respectively; similarly the public and private keys of process qe are named B_q and R_q respectively.

For process pe to change secret sq, the following four steps need to be performed. First, pe generates a new sq, and encrypts the concatenation of the old sq and the new sq using qe's public key B_q, and sends the result in a rqst message to qe. Second, when qe receives the rqst message, it decrypts the message contents using its private key R_q and obtains the old sq and the new sq. Then, qe checks that its current sq equals the old sq from the rqst message, and installs the new sq as its current sq, and sends a rply message containing the encryption of the new sq using pe's public key B_p. Third, pe waits until it receives a rply message from qe containing the new sq encrypted using B_p. Receiving this rply message indicates that qe has received the rqst message and has accepted the new sq. Fourth, if pe sends the rqst message to qe but does not receive the rply message from qe for some tr seconds, indicating that either the rqst message or the rply message was lost before it was received, then pe resends the rqst message to qe. Thus tr is an upper bound on the round trip time between pe and qe.

Note that the old secret (along with the new secret) is included in each rqst message and the new secret is included in each rply message to ensure that if an adversary modifies or replays rqst or rply messages, then each of these messages is detected and discarded by its receiving process (whether pe or qe).

Process pe has two variables sp and sq declared as follows.

```
var     sp :  integer
        sq :  array [0 .. 1] of integer
```

Similarly, process qe has an integer variable sq and an array variable sp.

In process pe, variable sp is used for storing the secret sp, variable sq[0] is used for storing the old sq, and variable sq[1] is used for storing the new sq. The assertion sq[0] ≠ sq[1] indicates that process pe has generated and sent the new secret sq, and that qe may not have received it yet. The assertion sq[0] = sq[1] indicates that qe has already received and accepted the new secret sq. Initially,

sq[0] in pe = sq[1] in pe = sq in qe, and
sp[0] in qe = sp[1] in qe = sp in pe.

Process pe can be defined as follows. (Process qe can be defined in the same way except that each occurrence of R_p in pe is replaced by an occurrence of R_q in qe, each occurrence of B_q in pe is replaced by an occurrence of B_p in qe, each occurrence of sp in pe is replaced by an occurrence of sq in qe, and each occurrence of sq[0] or sq[1] in pe is replaced by an occurrence of sp[0] or sp[1], respectively, in qe.)

```
process pe
inp     $R_p$   :  integer                       {private key of pe}
        $B_q$   :  integer                       {public key of qe}
        te      :  integer                       {time between secret exchanges}
        tr      :  integer                       {upper bound on round trip time}
var     sp      :  integer
        sq      :  array [0 .. 1] of integer     {initially sq[0] = sq[1] = sq in qe}
        d, e    :  integer
begin
        timeout   sq[0] = sq[1]  $\wedge$  (te hours passed since rqst message sent last) $\rightarrow$
            sq[1] := NEWSCR;
            e := NCR($B_q$, (sq[0]; sq[1]));
            send rqst(e) to qe

[]      rcv rqst(e) from qe $\rightarrow$
            (d, e) := DCR($R_p$ , e);
            if sp = d  $\vee$  sp = e     $\rightarrow$   sp := e;
                                          e := NCR($B_q$, sp);
                                          send rply(e) to qe
            [] sp $\neq$ d  $\wedge$  sp $\neq$ e   $\rightarrow$   {detect adversary} skip
```

```
          fi

[]     rcv rply(e) from qe →
          d := DCR($R_p$, e);
          if sq[1] = d →   sq[0] := sq[1]
          [] sq[1] ≠ d →   {detect adversary} skip
          fi

[]     timeout   sq[0] ≠ sq[1]  ∧  (tr seconds passed since rqst message sent last) →
          e := NCR($B_q$, (sq[0]; sq[1]));
          send rqst(e) to qe
end
```

The four actions of process pe use three functions NEWSCR, NCR, and DCR defined as follows. Function NEWSCR takes no arguments, and when invoked, it returns a fresh secret that is different from any secret that was returned in the past. Function NCR is an encryption function that takes two arguments, a key and a data item, and returns the encryption of the data item using the key. For example, execution of the statement

e := NCR(B_q, (sq[0]; sq[1]))

causes the concatenation of sq[0] and sq[1] to be encrypted using the public key B_q, and the result to be stored in variable e. Function DCR is a decryption function that takes two arguments, a key and an encrypted data item, and returns the decryption of the data item using the key. For example, execution of the statement

d := DCR(R_p, e)

causes the (encrypted) data item e to be decrypted using the private key R_p, and the result to be stored in variable d. As another example, consider the statement

(d, e) := DCR(R_p, e)

This statement indicates that the value of e is the encryption of the concatenation of two values (v_0; v_1) using key R_p. Thus, executing this statement causes e to be decrypted using key R_p, and the resulting first value v_0 to be stored in variable d, and the resulting second value v_1 to be stored in variable e.

To verify the correctness of the secret exchange protocol, refer to the state transition diagram of this protocol in Figure 2. This diagram has six nodes that represent all possible reachable states of the protocol. Every transition in the diagram stands for either a legitimate action (of process pe or process qe), or an illegitimate action of the adversary. For convenience, each transition is labeled by the message event that is executed during that transition. In particular, each transition has a label of the form

<event type> : <message type>

where <event type> is one of the following:

S stands for sending a message of the specified type

R stands for receiving a message of the specified type

L stands for losing a message of the specified type

M stands for modifying a message of the specified type

P stands for replaying a message of the specified type

The notation ch.pe.qe is used to denote the content of the channel from process pe to process qe.

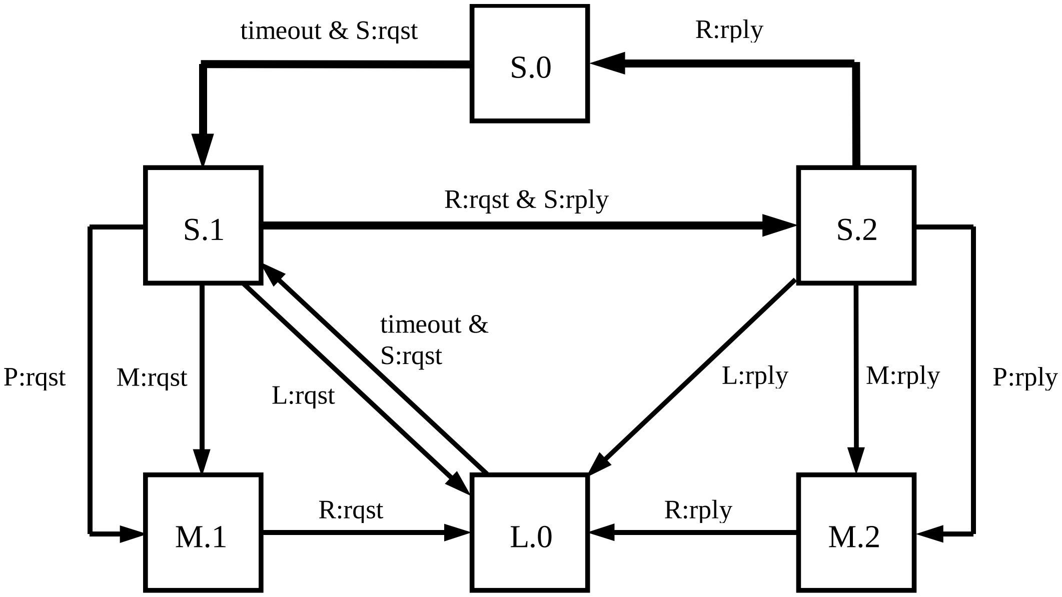


Figure 2. State transition diagram of the secret exchange protocol.

Initially, the protocol starts at a state S.0, where the two channels between processes pe and qe are empty and the values of variables sq[0], sq[1] in pe and variable sq in qe are the same. This state can be defined by the following predicate

S.0 = ch.pe.qe = < > $\wedge$ ch.qe.pe = < > $\wedge$ sq[0] in pe = sq[1] in pe = sq in qe

At state S.0, exactly one action, namely the first timeout action in process pe, is enabled for execution. Executing this action at state S.0 leads the protocol to state S.1 defined as follows:

S.1 = ch.pe.qe = <rqst(e)> $\wedge$ ch.qe.pe = < > $\wedge$ e = NCR(B_q, (sq[0]; sq[1])) $\wedge$
sq[0] in pe $\neq$ sq[1] in pe $\wedge$ sq[0] in pe = sq in qe

At state S.1, exactly one legitimate action, namely the receive action (that receives a rqst message) in process qe, is enabled for execution. Executing this action at state S.1 leads the protocol to state S.2 defined as follows:

S.2 = ch.pe.qe = < > $\wedge$ ch.qe.pe = <rply(e)> $\wedge$ e = NCR(B_p, sq) $\wedge$
sq[0] in pe $\neq$ sq[1] in pe $\wedge$ sq[1] in pe = sq in qe

At state S.2, exactly one legitimate action, namely the receive action (that receives a rply message) in process pe, is enabled for execution. Executing this action at state S.2 leads the protocol back to state S.0 defined above.

States S.0, S.1 and S.2 are called *good states* because the transitions between these states consist of executing the legitimate actions of the two processes. The sequence of transitions from state S.0 to state S.1, to state S.2, and back to state S.0 constitutes the *good cycle* of the protocol. If only legitimate actions of processes pe and qe are executed, the protocol will stay in this good cycle indefinitely. Next, we discuss the bad effects caused by the actions of an adversary, and how the protocol can recover from these effects.

First, the adversary can execute a message loss action at state S.1 or S.2. If the adversary executes a message loss action at state S.1 or S.2, the network moves to a state L.0 defined as follows:

L.0 = ch.pe.qe = < > $\wedge$ ch.qe.pe = < > $\wedge$
sq[0] in pe $\neq$ sq[1] in pe $\wedge$
(sq[0] in pe = sq in qe $\vee$ sq[1] in pe = sq in qe)

At state L.0, only the second timeout action in pe is enabled for execution, and executing this action leads the network back to state S.1.

Second, the adversary can execute a message modification action at state S.1 or S.2. If the adversary executes a message modification action at state S.1, the network moves to state M.1 defined as follows:

M.1 = ch.pe.qe = <rqst(e)> $\wedge$ ch.qe.pe = < > $\wedge$ e $\neq$ NCR(B_q, (sq[0]; sq[1])) $\wedge$
sq[0] in pe $\neq$ sq[1] in pe $\wedge$
(sq[0] in pe = sq in qe $\vee$ sq[1] in pe = sq in qe)

If the adversary executes a message modification action at state S.2, the network moves to state M.2 defined as follows:

M.2 = ch.pe.qe = < > $\wedge$ ch.qe.pe = <rply(e)> $\wedge$ e $\neq$ NCR(B_p, sq) $\wedge$
sq[0] in pe $\neq$ sq[1] in pe $\wedge$
(sq[0] in pe = sq in qe $\vee$ sq[1] in pe = sq in qe)

In either case, the protocol moves next to state L.0 and eventually returns to state S.1.

Third, the adversary can execute a message replay action at state S.1 or S.2. If the adversary executes a message replay action at state S.1, the network moves to state M.1. If the adversary executes a message replay action at state S.2, the network moves to state M.2. As shown above, the protocol eventually returns to state S.1.

From the state transition diagram in Figure 2, it is clear that each illegitimate action by the adversary will eventually lead the network back to state S.1, which is a good state. Once the network is in a good state, the network can progress in the good cycle. Hence the correctness of the secret exchange protocol is verified.

4. The Weak Integrity Protocol

The main idea of the weak integrity protocol is simple. Consider the case where a data(t) message, with t being the message text, is generated at a source src then transmitted through a sequence of adjacent routers r.1, r.2, …, r.n to a destination dst. When data(t) reaches the first router r.1, r.1 computes a digest d for the message as follows:

d := MD(t; scr)

where MD is the message digest function, (t; scr) is the concatenation of the message text t and the shared secret scr between r.1 and r.2 (provided by the secret exchange protocol in r.1). Then, r.1 adds d to the message before transmitting the resulting data(t, d) message to router r.2.

When the second router r.2 receives the data(t, d) message, r.2 computes the message digest using the secret shared between r.1 and r.2 (provided by the secret exchange process in r.2), and checks whether the result equals d. If they are unequal, then r.2 concludes that the received message has been modified, discards it, and reports an adversary. If they are equal, then r.2 concludes that the received message has not been modified and proceeds to prepare the message for transmission to the next router r.3. Preparing the message for transmission to r.3 consists of computing d using the shared secret between r.2 and r.3 and storing the result in field d of the data(t, d) message.

When the last router r.n receives the data(t, d) message, it computes the message digest using the shared secret between r.(n-1) and r.n and checks whether the result equals d. If they are unequal, r.n discards the message and reports an adversary. Otherwise, r.n sends the data(t) message to its destination dst.

Note that this protocol detects and discards every modified message. More importantly, it also determines the location where each message modification has occurred.

Process pw in the weak integrity protocol has two inputs sp and sq that pw reads but never updates. These two inputs in process pw are also variables in process pe, and pe updates them periodically, as discussed in the previous section. Process pw can be defined as follows. (Process qw is defined in the same way except that each occurrence of p, q, pw, qw, sp, and sq is replaced by an occurrence of q, p, qw, pw, sq, and sp, respectively.)

```
process pw
inp       sp        :  integer
```

```
        sq      :  array [0 .. 1] of integer
var     t, d    :  integer
begin
        rcv data(t, d) from qw →
            if MD(t; sq[0]) = d  ∨  MD(t; sq[1]) = d →        {defined later} RTMSG
            [] MD(t; sq[0]) ≠ d  ∧  MD(t; sq[1]) ≠ d →        {report adversary} skip
            fi

[]      true →
            {p receives data(t, d) from router other than q}
            {and checks that its message digest is correct}
            RTMSG

[]      true →
            {either p receives data(t) from an adjacent host or}
            {p generates the text t for the next data message}
            RTMSG
end
```

In the first action of process pw, if pw receives a data(t, d) message from qw while sq[0] ≠ sq[1], then pw cannot determine beforehand whether qw computed d using sq[0] or using sq[1]. In this case, pw needs to compute two message digests using both sq[0] and sq[1] respectively, and compare the two digests with d. If either digest equals d, then pw accepts the message. Otherwise, pw discards the message and reports the detection of an adversary.

The three actions of process pw use two functions named MD and NXT, and one statement named RTMSG. Function MD takes one argument, namely the concatenation of the text of a message and the appropriate secret, and computes a digest for that argument. Function NXT takes one argument, namely the text of a message (which we assume includes the message header), and computes the next router to which the message should be forwarded. Statement RTMSG is defined as follows.

```
if NXT(t) = p →        {accept message} skip
[] NXT(t) = q →        d := MD(t; sp);
                       send data(t, d) to qw
[] NXT(t) ≠ p  ∧  NXT(t) ≠ q →
                       {compute d as the message digest of}
                       {the concatenation of t and the secret}
                       {for sending data to NXT(t); forward}
                       {data(t, d) to router NXT(t)} skip
fi
```

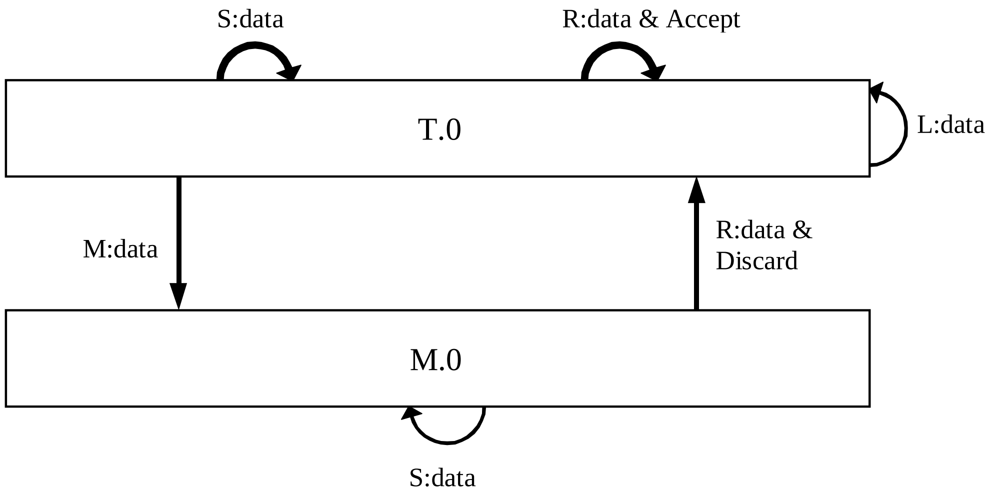
To verify the correctness of the weak integrity protocol, refer to the state transition diagram of this protocol in Figure 3, which considers the channel from process qw to process pw. (The channel from pw to qw, and the channels from pw to any other weak integrity process in an adjacent router of p, can be verified in the same way.) This diagram has two nodes that represent all possible reachable states of the protocol. Every transition in the diagram stands for either a legitimate action (of process pw or process qw), or an illegitimate action of the adversary.

Note that because the weak integrity protocol operates below the secret exchange protocol in the protocol stack, we can assert that (sq in qw = sq[0] in pw $\vee$ sq in qw = sq[1] in pw) is an invariant in every state of the weak integrity protocol. We denote this invariant as I in the specification in Figure 3. Also note that the notation Head(data(t, d)) in the specification in Figure 3 is a predicate whose value is true iff data(t, d) is the head message of the specified channel.

Initially, the protocol starts at state T.0. At state T.0, two legitimate actions, namely the send action in qw that sends a data message, and the receive action in pw that receives a data message, can be executed. Executing either one of the two actions at state T.0 keeps the protocol in state T.0.

States T.0 is the only good state in the weak integrity protocol. The sequence of the transitions from state T.0 to state T.0 constitutes the good cycle of the protocol. If only legitimate actions of processes pw and qw are executed, the protocol will stay in this good cycle indefinitely. Next, we discuss the bad effects caused by the actions of an adversary, and how the protocol can recover from these effects.

First, the adversary can execute a message loss action at state T.0. If the adversary executes a message loss action at state T.0, the predicate that for every data message data(t, d) in the channel from qw to pw, d = MD(t; sq), still holds. Therefore, the protocol stays at state T.0.



$\text{T.0} = \quad I \wedge (\forall \text{data}(t, d) \text{ message in ch.qw.pw}, \quad d = \text{MD}(t; sq))$

$\text{M.0} = \quad I \wedge (\forall \text{data}(t, d) \text{ message in ch.qw.pw},$
$\quad (\neg \text{Head}(\text{data}(t, d)) \Rightarrow d = \text{MD}(t; sq)) \wedge$
$\quad (\text{Head}(\text{data}(t, d)) \Rightarrow d \neq \text{MD}(t; sq)))$
where
$I \quad = \quad sq \text{ in } qw = sq[0] \text{ in } pw \vee sq \text{ in } qw = sq[1] \text{ in } pw$

Figure 3. State transition diagram of the weak integrity protocol.

Second, the adversary can execute a message modification action at state T.0. If the adversary executes a message modification at state T.0, the protocol moves to state M.0. The receive and discard action executed by pw at state M.0 leads the protocol back to state T.0.

From the state transition diagram, it is clear that each illegitimate action by the adversary will eventually lead the protocol back to T.0, which is a good state. Once the protocol is in a good state, the protocol can progress in the good cycle. However, the weak integrity protocol, while being able to detect and discard all modified messages, cannot detect some replayed messages. In the next section, we introduce the strong integrity protocol that is capable of detecting and discarding all modified and replayed messages.

5. The Strong Integrity Protocol

The weak integrity protocol in the previous section can detect message modification but not message replay. In this section, we discuss how to strengthen this protocol to make it detect message replay as well. We present the strong integrity protocol in two steps. First, we present a protocol that uses “soft sequence numbers” to detect and discard replayed data messages. Second, we show how to combine this protocol with the weak integrity protocol (in the previous section) to form the strong integrity protocol.

Consider a protocol that consists of two processes u and v. Process u continuously sends data messages to process v. Assume that there is an adversary that attempts to disrupt the communication between u and v by inserting (i.e. replaying) old messages in the message stream from u to v. In order to overcome this adversary, process u attaches an integer sequence number s to every data message sent to process v. To keep track of the sequence numbers, process u maintains a variable nxt that stores the sequence number of the next data message to be sent by u and process v maintains a variable exp that stores the sequence number of the next data message to be received by v.

To send the next data(s) message, process u assigns s the current value of variable nxt, then increments nxt by one. Assume that no more than L consecutive messages can get lost in transit. When process v receives a data(s) message, v compares its variable exp with s. If $exp \le s \le exp + L$, then v accepts the received data(s) message and assigns exp the value $s + 1$; otherwise v discards the data(s) message.

Correctness of this protocol is based on the observation that the predicate $exp \le nxt$ holds at each (reachable) state of the protocol. However, if due to some fault (for example an accidental resetting of the values of variable nxt) the value of exp becomes much larger than value of nxt, then all the data messages that u sends from this point on will be wrongly discarded by v until nxt becomes equal to exp. Next, we describe how to modify this protocol such that the number of data(s) messages, that can be wrongly discarded when the synchronization between u and v is lost due to some fault, is at most N, for some chosen integer N that is much larger than one.

The modification consists of adding to process v two variables c and cmax, whose values are in the range 0..N-1. When process v receives a data(s) message, v compares the values of c and cmax. If c ≠ cmax, then process v increments c by one (mod N) and proceeds as before (namely either accepts the data(s) message if exp ≤ s ≤ exp + L, or discards the message if exp > s or exp + L < s). Otherwise, v accepts the message, assigns c the value 0, and assigns cmax a random integer in the range 0..N-1.

This modification achieves two objectives. First, it guarantees that process v never discards more than N data messages when the synchronization between u and v is lost due to some fault. Second, it ensures that the adversary cannot predict the instants when process v is willing to accept any received data message, and so cannot exploit such predictions by sending replayed data messages at those instants.

Formally, process u and v in this protocol can be defined as follows.

```
process u
var     nxt       :  integer                {sequence number of next sent message}
begin
        true →    send data(nxt) to v;   nxt := nxt + 1
end

process v
inp     N         :  integer
        L         :  integer
var     s         :  integer                {sequence number of received message}
        exp       :  integer                {sequence number of next expected message}
        c, cmax   :  0 .. N – 1
begin
        rcv data(s) from u →
            if  (s < exp  ∨  s > exp + L)  ∧  c ≠ cmax →
                          {reject message; report an adversary}
                          c := (c + 1) mod N
            []  (exp ≤ s ≤ exp + L)  ∨  c = cmax →
                          {accept message}
                          exp := s + 1;
                          if  c ≠ cmax →  c := (c + 1) mod N
                          []  c = cmax →  c := 0;
                                          cmax := RANDOM(0, N – 1)
                          fi
            fi
end
```

Processes u and v of the soft sequence number protocol can be combined with process pw of the weak integrity protocol to construct process ps of the strong integrity protocol. A main difference between processes pw and ps is that pw exchanges messages of the form data(t, d), whereas ps exchanges messages of the form data(s, t, d), where s is the message sequence number computed according to the soft sequence number protocol, t is the message text, and d is the message digest computed over the concatenation (s; t; scr) of s, t, and the shared secret scr. Process ps in the strong integrity protocol can be defined as follows. (Process qs can be defined in the same way.)

```
process ps
inp     sp          :  integer
        sq          :  array [0 .. 1] of integer
        N           :  integer
        L           :  integer
var     s, t, d     :  integer
        exp, nxt    :  integer
        c, cmax     :  0 .. N – 1
begin
        rcv data(s, t, d) from qs →
            if MD(s; t; sq[0]) = d  ∨  MD(s; t; sq[1]) = d →
                    if   (s < exp  ∨  s > exp + L)  ∧  c ≠ cmax →
                                {reject message; report an adversary}
                                c := (c + 1) mod N
                    []   (exp ≤ s ≤ exp + L)  ∨  c = cmax →
                                {accept message}
                                exp := s + 1;
                                if  c ≠ cmax →  c := (c + 1) mod N
                                []  c = cmax →  c := 0;
                                                cmax := RANDOM(0, N – 1)
                                fi
                    fi
            [] MD(s; t; sq[0]) ≠ d  ∧  MD(s; t; sq[1]) ≠ d →
                    {report an adversary} skip
            fi

[]      true →
            {p receives a data(s, t, d) from a router other than q and checks that}
            {its encryption is correct and its sequence number is within range}
            RTMSG

[]      true →
            {either p receives a data(t) from adjacent host or}
            {p generates the text t for the next data message}
            RTMSG
```

```
end
```

The first and second actions of process ps have a statement RTMSG that is defined as follows.

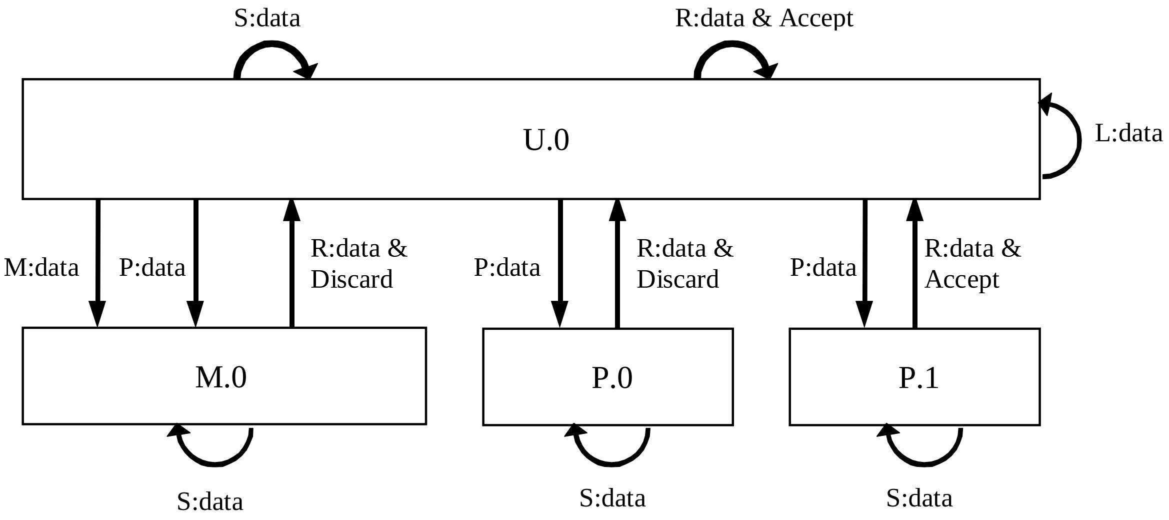
```
if NXT(t) = p →        {accept message} skip
[] NXT(t) = q →        d := MD(nxt; t; sp);
                       send data(nxt, t, d) to qs;
                       nxt := nxt + 1
[] NXT(t) ≠ p ∧ NXT(t) ≠ q →
                       {compute next soft sequence number s;}
                       {compute d as the message digest of the}
                       {concatenation of snxt, t and the secret}
                       {for sending data to NXT(t); forward}
                       {data(s, t, d) to router NXT(t)} skip
fi
```

To verify the correctness of the strong integrity protocol, refer to the state transition diagram of this protocol in Figure 4, which considers the channel from process qs to process ps. (The channel from ps to qs, and the channels from ps to any other strong integrity process in an adjacent router of p, can be verified in the same way.) This diagram has four nodes that represent all possible reachable states of the protocol. Every transition in the diagram stands for either a legitimate action (of process ps or process qs), or an illegitimate action of the adversary.

Note that because the strong integrity protocol operates below the secret exchange protocol in the protocol stack, we can assert that (sq in qs = sq[0] in ps $\vee$ sq in qs = sq[1] in ps) is an invariant in every state of the strong integrity protocol. We denote this invariant as I in the specification in Figure 4.

Initially, the protocol starts at state U.0. At state U.0, two legitimate actions, namely the send action in qs that sends a data message, and the receive action in ps that receives a data message, can be executed. Executing either one of the two actions at state U.0 keeps the protocol in state U.0.

States U.0 is the only good state in the strong integrity protocol. The sequence of the transitions from state U.0 to state U.0 constitutes the good cycle of the protocol. If only legitimate actions of processes ps and qs are executed, the protocol will stay in this good cycle indefinitely. Next, we discuss the bad effects caused by the actions of an adversary, and how the protocol can recover from these effects.



$U.0 = I \land (\forall data(s, t, d)$ message in ch.qs.ps,
$d = MD(s; t; sq) \land (Head(data(s, t, d)) \Rightarrow exp \le s \le exp + L$ in ps))

$M.0 = I \land (\forall data(s, t, d)$ message in ch.qs.ps,
$(\neg Head(data(s, t, d)) \Rightarrow d = MD(s; t; sq)) \land$
$(Head(data(s, t, d)) \Rightarrow d \neq MD(s; t; sq)))$

$P.0 = I \land (\forall data(s, t, d)$ message in ch.qs.ps,
$d = MD(s; t; sq) \land$
$(Head(data(s, t, d)) \Rightarrow s < exp \lor s > exp + L$ in ps) $\land\ c \neq cmax$ in ps)

$P.1 = I \land (\forall data(s, t, d)$ message in ch.qs.ps,
$d = MD(s; t; sq) \land$
$(Head(data(s, t, d)) \Rightarrow s < exp \lor s > exp + L$ in ps) $\land\ c = cmax$ in ps)

where
$I =$ sq in qs = sq[0] in ps $\lor$ sq in qs = sq[1] in ps

Figure 4. State transition diagram of the strong integrity protocol.

First, the adversary can execute a message loss action at states U.0. If the adversary executes a message loss action at state U.0, the predicate that for every data message data(s, t, d) in the channel from qs to ps, d = MD(s; t; sq), still holds. Therefore, the protocol stays at state U.0.

Second, the adversary can execute a message modification action at state U.0 causing the protocol to move to state M.0. The receive and discard action executed by ps at state M.0 leads the protocol back to state U.0.

Third, the adversary can execute a message replay action at state U.0. There are two cases to consider. First, if the replayed message data(s, t, d) is too old such that the secret used to compute the message digest is different from the current value of input sq in process qs, then the protocol moves to state M.0, and later returns to state U.0 as discussed above. Second, if the replayed message data(s, t, d) is recent such that the secret used to compute the message digest is equal to the current value of input sq in process qw, then the protocol moves either to state P.0 or to state P.1. With a high probability of (cmax – 1) / cmax, the protocol moves to state P.0, and the replayed message will be received and discarded by ps because the value of field s in the message tells that the message is replayed. With a probability of 1 / cmax, the protocol moves to state P.1, and the replayed message will be received and accepted. In both cases the protocol returns to state U.0.

From the state transition diagram, it is clear that each illegitimate action by the adversary will eventually lead the protocol back to U.0, which is a good state. Once the protocol is in a good state, the protocol can progress in the good cycle. Moreover, if the adversary replays a recent data message, the replayed message will be detected and discarded with the high probability (cmax – 1) / cmax.

6. Implementation Considerations

In this section, we discuss several issues concerning the implementation of hop integrity protocols presented in the last three sections. In particular, we discuss acceptable values for the inputs of each of these protocols.

There are four inputs in the secret exchange protocol in Section 3. They are R_p, B_q, te and tr. Input R_p is a private key for router p, and input B_q is a public key for router q.

These are long-term keys that remain fixed for long periods of time (say one to three months), and can be changed only off-line and only by the system administrators of the two routers. Thus, these keys should consist of a relatively large number of bytes, say 128 bytes (1024 bits) each. There are no special requirements for the encryption and decryption functions that use these keys in the secret exchange protocol.

Input te is the time period between two successive secret exchanges between pe and qe. This time period should be small so that an adversary does not have enough time to deduce the secrets sp and sq used in computing the integrity checks of data messages. It should also be large so that the overhead that results from the secret exchanges is reduced. An acceptable value for te is around 4 hours.

Input tr is the time-out period for resending a rqst message when the last rqst message or the corresponding rply message was lost. The value of tr should be an upper bound on the round-trip delay between the two adjacent routers. If the two routers are connected by a high speed Ethernet, then an acceptable value of tr is around 4 seconds.

Next, we consider the two inputs sp and sq and function MD used in the integrity protocols in Sections 4 and 5. Inputs sp and sq are short-lived secrets that are updated every 4 hours. Thus, this key should consist of a relatively small number of bytes, say 8 bytes. Function MD is used to compute the digest of a data message. Function MD is computed in two steps as follows. First, the standard function MD5 [Riv92] is used to compute a 16-byte digest of the data message. Second, the first 4 bytes from this digest constitute our computed message digest.

The soft sequence numbers in Section 5 can be recycled provided that not each of the sequence numbers has been used at least once in time period te. In a usual Ethernet, at most 800 messages can be sent in a second, thus at most 11,520,000 messages can be sent in a period of 4 hours. Using 4 bytes to store the soft sequence numbers is a proper choice with considerations of covering the maximum number of consumed sequence numbers in time period te and aligning with the original IP header.

As discussed in Section 5, input N needs to be much larger than 1. For example, N can be chosen 200. In this case, the maximum number of messages that can be discarded wrongly whenever synchronization between two adjacent routers is lost is 200, and the probability that an adversary who replays an old message will be detected is 99 percent.

The message overhead of the strong integrity protocol is about 8 bytes per data message: 4 bytes for storing the message digest, and 4 bytes for storing the soft sequence number of the message.

7. Concluding Remarks

In this paper, we introduced the concept of hop integrity in computer networks. A network is said to provide hop integrity iff whenever a router p receives a message supposedly from an adjacent router q, router p can check whether the received message was indeed sent by q or was modified or replayed by an adversary that operates between p and q.

The effectiveness of hop integrity is apparent in those situations where ingress filtering is not effective. For example, ingress filtering can detect and discard messages with wrongly recorded sources at the network boundary, but cannot do so between adjacent routers in the middle of the network. By contrast, hop integrity can detect and discard messages with wrongly recorded source between adjacent routers in the middle of the network.

Moreover, ingress filtering is not compatible with mobile IP. A message sent by a mobile node and forwarded by the foreign agent (of this mobile node) will be filtered out by the next router because the recorded source of the message seems wrong to the router. By contrast, hop integrity can guarantee that every message forwarded by the foreign agent will be accepted by the router. (Reverse tunneling [Mon98] was proposed to remedy this problem, but the cost of using reverse tunneling is high because every message that is sent by a mobile node has to be tunneled back to the home agent of the mobile node before the message can be forwarded.)

We presented three protocols that can be used to make any computer network provide hop integrity. These three protocols are a secret exchange protocol (in Section 3), a weak integrity protocol (in Section 4), and a strong integrity protocol (in Section 5).

These three protocols have several novel features that make them correct and efficient. First, whenever the secret exchange protocol attempts to change a secret, it keeps both the old secret and the new secret until it is certain that the integrity check of any future message will not be computed using the old secret. Second, the integrity protocol computes a digest at every router along the message route so that the location of any occurrence of message modification can be determined. Third, the strong integrity protocol uses soft sequence numbers to make the protocol tolerate any loss of synchronization.

It is possible to reduce the overhead induced by the three protocols as follows. If in a network some hops are assured to be adversary-proof (for example the hops between core routers), then hop integrity does not need to be implemented over these hops. When a router needs to forward a message over an adversary-proof hop, it just follows the same procedure as in normal IP.

All three protocols are stateless, require small overhead at each hop, and do not constrain the network protocol in any way. Thus, we believe that they are compatible with IP in the Internet, and it remains to estimate or measure the performance of IP when augmented with these protocols.

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