

Rushing Attacks and Defense in Wireless Ad Hoc Network Routing Protocols *

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ABSTRACT

In an *ad hoc network*, mobile computers (or nodes) cooperate to forward packets for each other, allowing nodes to communicate beyond their direct wireless transmission range. Many of the proposed routing protocols for ad hoc networks operate in an *on-demand* fashion, as on-demand routing protocols have been shown to often have lower overhead and faster reaction time than other types of routing based on periodic (proactive) mechanisms. Significant attention recently has been devoted to developing secure routing protocols for ad hoc networks, including a number of secure on-demand routing protocols, that defend against a variety of possible attacks on network routing. In this paper, we present the *rushing attack*, a new attack that results in denial-of-service when used against *all* previous on-demand ad hoc network routing protocols. For example, DSR, AODV, and secure protocols based on them, such as Ariadne, ARAN, and SAODV, are unable to discover routes longer than two hops when subject to this attack. This attack is also particularly damaging because it can be performed by a relatively weak attacker. We analyze why previous protocols fail under this attack. We then develop *Rushing Attack Prevention (RAP)*, a generic defense against the rushing attack for on-demand protocols. RAP incurs *no cost* unless the underlying protocol fails to find a working route, and it provides provable security properties even against the strongest rushing attackers.

Categories and Subject Descriptors: C.0 [Computer-Communications Networks]: Security and protection; C.2.2 [Network Protocols]: Routing Protocols

General Terms: Security, Performance

Keywords: Ad hoc network routing, security, routing, rushing

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1. INTRODUCTION

An *ad hoc network* is a collection of mobile computers (or nodes) that cooperate to forward packets for each other to extend the limited transmission range of each node's wireless network interface. A routing protocol in such a network finds routes between nodes, allowing a packet to be forwarded through other network nodes towards its destination. In contrast to traditional network routing protocols, for example for wired networks, ad hoc network routing protocols must adapt more quickly, since factors such as significant node movement and changing wireless conditions may result in rapid topology change.

This problem of routing in ad hoc networks is an important one, and has been extensively studied. This study has resulted in several mature protocols [9, 22, 32, 34]. Ad hoc networks are targeted at environments where communicating nodes are mobile, or where wired network deployment is not present or not economical. Many of these applications may run in untrusted environments and may therefore require the use of a secure routing protocol. Furthermore, even when the presence of an attacker is not foreseen, a secure ad hoc network routing protocol can also provide resilience against misconfigured nodes. In the current Internet, for example, misconfigured routing tables contribute to the majority of routing instabilities [28]. Similarly, a software or hardware failure should cause only the affected node to fail, and not perturb the stability of routing in the remainder of the network. Mission or safety-critical networks can use secure ad hoc routing protocols so that configuration errors, software bugs, or hardware failures do not disturb routing at other nodes. As a result, several secure ad hoc network routing protocols have been proposed [6, 14, 18, 33, 38, 41, 47].

In this paper, we present a new attack, the *rushing attack*, which results in denial-of-service when used against all previously published on-demand ad hoc network routing protocols. Specifically, the rushing attack prevents previously published secure on-demand routing protocols to find routes longer than two-hops (one intermediate node between the initiator and target).

Because on-demand protocols generally have lower overhead and faster reaction time than other types of routing based on periodic (proactive) mechanisms, on-demand protocols are better suited for most applications. To defend this important class of protocols against the rushing attack, we develop a generic secure Route Discovery component, called *Rushing Attack Prevention (RAP)*, that can be applied to any existing on-demand routing protocol to allow that protocol to resist the rushing attack.

Our main contributions in this paper are the presentation of the rushing attack, the development and analysis of our new secure Route Discovery component that demonstrates that it is possible to secure against the rushing attack, and a general design that uses this component to secure any on-demand Route Discovery mecha-

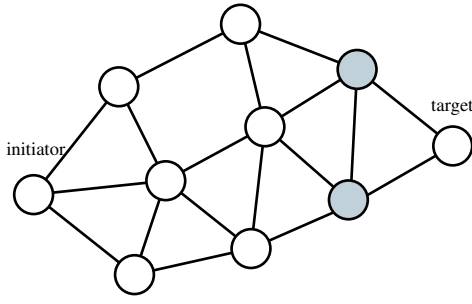


Figure 1: Example network illustrating the rushing attack.

nism against the rushing attack.

In Section 2 of this paper, we introduce the rushing attack. Section 3 details our assumptions. Section 4 describes our Secure Neighbor Detection and Secure Route Discovery procedures, and Section 5 presents two evaluations of our Route Discovery component: a simulation study of the performance of our mechanisms, and an analytical evaluation that gives a conservative lower bound on the probability that our protocols discover a working route when subject to this attack. In Section 6, we discuss related work, and in Section 7, we present conclusions.

2. THE RUSHING ATTACK AGAINST AD HOC NETWORK ROUTING PROTOCOLS

We introduce here a new attack, which we call *the rushing attack*, that acts as an effective denial-of-service attack against all currently proposed on-demand ad hoc network routing protocols, including protocols that were designed to be secure. In an on-demand protocol, a node needing a route to a destination floods the network with ROUTE REQUEST packets in an attempt to find a route to the destination. To limit the overhead of this flood, each node typically forwards only one ROUTE REQUEST originating from any Route Discovery. In particular, existing on-demand routing protocols, such as AODV [34], DSR [22], LAR [25], Ariadne [18], SAODV [47], ARAN [41], AODV secured with SUCV [6], and SRP [33], only forward the REQUEST that arrives *first* from each Route Discovery. In the rushing attack, the attacker exploits this property of the operation of Route Discovery.

We now describe the rushing attack in terms of its effect on the operation of DSR Route Discovery [20, 21, 22]; other protocols such as AODV [35], Ariadne [18], SAODV [47], and ARAN [41] are vulnerable in the same way. In the network shown in Figure 1, the initiator node initiates a Route Discovery for the target node. If the ROUTE REQUESTs for this Discovery forwarded by the attacker are the first to reach each neighbor of the target (shown in gray in the figure), then any route discovered by this Route Discovery will include a hop through the attacker. That is, when a neighbor receives the rushed REQUEST from the attacker, it forwards that REQUEST, and will not forward any further REQUESTs from this Route Discovery. When non-attacking REQUESTs arrive later at these nodes, they will discard those legitimate REQUESTs. As a result, the initiator will be unable to discover any usable routes (i.e., routes that do not include the attacker) containing at least two hops (three nodes).

In general terms, an attacker that can forward ROUTE REQUESTs more quickly than legitimate nodes can do so, can increase the probability that routes that include the attacker will be discovered rather than other valid routes. Whereas the discussion above has used the case of nodes that forward only the *first* ROUTE REQUEST

from any Route Discovery, the rushing attack can also be used against any protocol that predictably forwards *any* particular REQUEST for each Route Discovery.

A rushing attacker need not have access to vast resources. On-demand routing protocols delay ROUTE REQUEST forwarding in two ways. First, Medium Access Control (MAC) protocols generally impose delays between when the packet is handed to the network interface for transmission and when the packet is actually transmitted. In a MAC using time division, for example, a node must wait until its time slot to transmit, whereas in a MAC using carrier-sense multiple access, a node generally performs some type of backoff to avoid collisions; protocols like IEEE 802.11 also impose an interframe spacing time before transmission actually begins. Second, even if the MAC layer does not specify a delay, on-demand protocols generally specify a delay between receiving a REQUEST and forwarding it, in order to avoid collisions of the REQUEST packets. In particular, because REQUEST packets are broadcast, and collision detection for broadcast packets is difficult, routing protocols often impose a randomized delay in REQUEST forwarding. An attacker ignoring delays at either the MAC or routing layers will generally be preferred to similarly situated non-attacking nodes. One way to thwart an attacker that rushes in this way is to remove these delays at both the MAC and routing layers, but this approach does not work against all types of rushing attackers and is not general. For example, in a dense network using a CSMA MAC layer, if a node *A* initiates a Route Discovery, and *B* is two hops away from *A*, and *C* and *D* are neighbors of both *A* and *B*, then then *B* will likely not receive the ROUTE REQUEST due to a collision between REQUESTs forwarded by *C* and *D*. In a dense network, such collisions may often prevent the discovery of any nontrivial routes (routes longer than a direct link), which is even more severe than the rushing attack, which prevents the discovery of routes longer than two hops.

Another way that a relatively weak attacker can obtain an advantage in forwarding speed is to keep the network interface transmission queues of nearby nodes full. For example, if each node processes the packets it receives in order, and an inefficient REQUEST authentication mechanism is used, the attacker can keep other nodes busy authenticating REQUESTs containing bogus authentication, thus slowing their ability to forward legitimate REQUESTs. Protocols employing public key techniques are particularly susceptible to these attacks, since they require substantial computation to validate each received REQUEST.

A relatively weak attacker can also achieve faster transit of its REQUEST packets by transmitting them at a higher wireless transmission power level, thus reducing the number of nodes that must forward that REQUEST to arrive at the target. Since packet transit time at each hop is dominated by the processing time at the forwarding node, reducing the path to the target by just one hop is likely to provide a significant latency advantage, thus strengthening the attackers position.

A more powerful rushing attacker may employ a wormhole [15] to rush packets. In this case, the attacker simply forwards all control packets (but not data packets) received at one node (the attacker) to another node in the network (e.g., a second attacker). This forms a tunnel in the network, where packets reaching one end of the tunnel are broadcast out the other end. If the tunnel provides significantly faster transit than legitimate forwarders, nodes near one end of the tunnel generally will be unable to discover working routes to the other end of the tunnel, since it will generally discover routes through the tunnel. In general, a wired tunnel (in which the two attackers have a wired connection between themselves) will provide faster transit than native wireless (multihop) forwarding, since

node processing delay in forwarding is much longer than the propagation time.

The rushing attack applies to all proposed on-demand protocols because such protocols must limit the number of packets that any node will transmit in response to a single Route Discovery. Currently proposed protocols choose to forward at most one REQUEST for each Discovery; any protocol that allows an attacker to predict which ROUTE REQUEST(s) will be chosen for forwarding at each hop will be vulnerable to some variant of the rushing attack.

3. ASSUMPTIONS

3.1. Network Assumptions

We make the common assumption that most network links are bidirectional. More specifically, we require that the network remain connected when unidirectional links are ignored. Our Secure Neighbor Detection protocol rejects unidirectional links, so underlying routing protocols can assume that the network is free of unidirectional links. If another Secure Neighbor Detection technique is used, and that technique supports unidirectional links, then the ability of our Secure Route Discovery mechanism to discover and use unidirectional links is limited only by the underlying routing protocol.

Wireless physical layers for sending data from one node to another are often vulnerable to jamming. Mechanisms such as spread spectrum modulation [39], or directional antennas have been extensively studied as means of improving resistance to physical jamming. In addition, an effective jamming attack usually requires additional hardware; in contrast, a rushing attack is much simpler to do because the attacker can use the same hardware as legitimate nodes. An attacker can even remotely break into a legitimate node and perform these attacks. Moreover, the rushing attack allows for far more selective denial-of-service, and is thus harder to detect. Jamming attacks are relatively broad (they deny service to a large number of participants) and are thus also easier to detect. Though a jamming attack is also an important denial-of-service attack, we present mechanisms to defend against the rushing attack because we believe that the rushing attack is more easily performed.

Medium Access Control protocols are also often vulnerable to attack. For example, in IEEE 802.11, an attacker can paralyze nodes in its neighborhood by sending Clear-To-Send (CTS) frames periodically, setting the “Duration” field of each frame equal to the interval between such frames [18]. Less sophisticated Medium Access Control protocols, such as ALOHA and Slotted ALOHA [1], are not vulnerable to such attacks but have lower efficiency. In this paper, we disregard attacks on Medium Access Control protocols.

Prior work has shown that ad hoc network routing in general does not scale well [11]. Most existing simulation of ad hoc network routing protocols consider scenarios of 50 to 500 nodes. In this work, we focus on such medium-sized networks, and will not consider scalability issues; however, we believe that mechanisms such as clustering, which improve the scalability of other on-demand ad hoc network routing protocols, can also improve the scalability of our approach.

3.2. Security Assumptions and Key Setup

The protocols discussed in this paper require an instantly-verifiable broadcast authentication protocol, for which we use a digital signature. However, any signature used should be able to keep up with verification at line speed, to avoid a denial-of-service attack where an attacker overwhelms the victim by flooding it with bogus messages. One example of a protocol which should be fast enough on many nodes is the HORS one-time signature by Reyzin and

Reyzin [40]. We use the constructions of the BiBa [37] one-time signature in conjunction with the HORS one-time signature to design an efficient instantly-verifiable broadcast authentication protocol. We also use a Merkle hash tree [30] to generate one signature over multiple messages, such that each message is independently verifiable. As used in our simulation evaluation, HORS requires an average of 156,760 hashes per second to sign and verify all messages in a 100 node network, a rate easily achievable even by PDAs. Should say how much of the PDA CPU is used. We assume that the keys necessary for broadcast authentication are distributed in advance; a number of techniques for distributing such information have been proposed [2, 18, 19, 26, 44, 48]. To escape the circular dependency of secure routing and key distribution, Hu et al propose a simple routing protocol that discovers a route to a trusted third party, which can in turn bootstrap the initial keys [18].

If a wormhole attack, in which an attacker selectively tunnels packets from one place in the network to another, is considered a possible threat, our Secure Neighbor Detection requires a mechanism to detect such a tunnel between any two legitimate nodes. A number of mechanisms for preventing the wormhole attack, such as TIK, geographical leashes and RF watermarking, have been proposed. Depending on the mechanism used to implement packet leashes, this requirement benefit other parts of the protocol: TIK [15], for example, authenticates each packet in a lightweight manner, thus protecting the more expensive signature verification from a denial-of-service attack. In particular, if a node A receives an authenticated packet containing a bogus signature from node B , then A can lower the priority with which it checks signatures sent by B . As a result, an attacker can only cause each node to verify one bogus signature for each node compromised by that attacker.

We do not assume tamper-proof hardware; the attacker can thus compromise nodes and steal their cryptographic keys. We assume a powerful attacker, which we call *coordinated attacker*. This is an attacker that compromised multiple nodes (and thus knows all their cryptographic keys), with a fast channel to route packets amongst themselves.

4. SECURE ROUTING REQUIREMENTS AND PROTOCOL

In this section, we describe a generic protection mechanism that prevents the rushing attack. We also describe a technique to secure any protocol using an on-demand Route Discovery mechanism.

We design two mechanisms that are both required to defend against the rushing attack: (1) secure neighbor discovery, ensuring that the two neighboring nodes really are neighbors within communication range (after the sender is certain that the next hop is indeed within range, it signs a route delegation, and after the receiver is certain that the sender is in range, it signs an acceptance message); (2) probabilistic selection of route discovery message, replacing traditional duplicate suppression (in duplicate suppression, the receiver of a route discovery message always uses the first arriving message). Figure 2 shows this basic design. This figure should be changed, doesn't currently make much sense.

4.1. Notation

We use the following notation:

- A or B denote communicating nodes.
- $A : \eta \xleftarrow{R} \{0, 1\}^\ell$ denotes that node A randomly selects an ℓ -bit long nonce η .

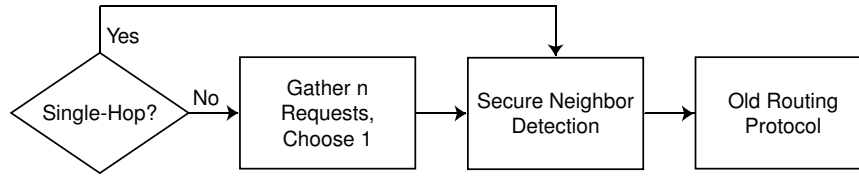


Figure 2: Our design to secure a protocol against the rushing attack.

- $A \rightarrow B : \langle M, H(A || \eta) \rangle$ means that node A sends B the message M and the hash of A 's identifier concatenated with the nonce η .
- $A \rightarrow * : \langle M, \Sigma_M \rangle$ means that node A broadcasts message M with its signature Σ_M .

4.2. Secure Neighbor Detection

One common scenario of the rushing attack is where an attacker forwards a ROUTE REQUEST beyond the radio transmission range, thus effectively suppressing subsequent packets. In this section we present a secure Neighbor Detection protocol that ensures to both the sender and the receiver of a ROUTE REQUEST that the other party is within direct communication range.

The functionality of *Neighbor Detection*, in which two nodes detect a bidirectional link between themselves, is present in almost every routing protocol. For example, a node participating in a periodic protocol generally broadcasts advertisements, allowing its neighbors to detect it. Most on-demand routing protocols, on the other hand, perform Neighbor Detection implicitly. In those protocols, a node receiving a ROUTE REQUEST considers itself to be a neighbor of the transmitter. When that node propagates the REQUEST, it claims a link between the transmitter and the recipient. Unfortunately, this does not prevent an attacker node receiving a REQUEST from simply replaying it. In addition, the address of the previous node is unauthenticated, so an attacker can claim to be any node propagating a REQUEST, and the next hop will trust that information (we call this the *Repeater Attack*). This repeater attack is serious because two nodes that are not within communication range believe to be neighbors, thus the link can disappear at the will of the repeater node. The repeater attack is an instance of a wormhole attack [16]. The Sybil attack [10] makes these attacks potentially more dangerous, as an attacker may fake additional non-existing nodes. Actually, is the Sybil attack really an issue here, it seems not to be, but we should think about instances where it is an issue.

Requirements for Secure Neighbor Detection. Two nodes detect themselves as neighbors only if they are within transmission range. The secure Neighbor Detection protocol thus prevents an attacker from: (1) introducing two nodes that are not in transmission range as neighbors; and (2) claiming that it is a neighbor of another node without being able to hear packets directly from that node. From the first requirement it follows that an attacker should not be able to *tunnel* a neighbor solicitation from one compromised node to another uncompromised node. The second requirement demands that a node needs to hear the neighbor solicitation, otherwise it cannot claim to be a neighbor. Finally, the protocol should not introduce a denial-of-service opportunity, for example by flooding nodes with neighbor requests.

Our Secure Neighbor Detection Protocol. We present a secure Neighbor Detection protocol that ensures to the initiator and the responder that they are both within communication range. Assuming negligible MAC protocol delays, we design a simple three-round

mutual authentication protocol that uses tight delay timing to ensure that the other party is within communication range. Btw, our protocol has the problem that if all the neighbors immediately respond to the initial broadcast message, their responses will collide at the initiator, no? We should maybe do an initial neighbor poll, then do a one-by-one neighbor detection? Our secure Neighbor Detection protocol requires three rounds. First, the initiating node sends a Neighbor Solicitation packet, either by unicasting that packet to a specific neighbor, or by broadcasting the packet. Next, a node receiving the Neighbor Solicitation packet sends a Neighbor Reply packet. Finally, the initiator sends a Neighbor Verification, which includes broadcast authentication of a timestamp and the link from the source to the destination. Figure 3 shows an example of the protocol. Note that to ensure freshness of the reply messages, we use nonces η_1 and η_2 . The initiator picks η_1 at random (of sufficient length to keep the probability negligible that an attacker could guess it) and is thus certain that the reply message is fresh if the received nonce matches η_1 . The measured delay between sending the first message and receiving the second message ensures an upper bound on the distance of the neighbor: given delay Δ , the neighbor node can be at most at a distance of $\Delta/2 \cdot c$, where c is the speed of light. This is accurate if the processing time of the response message is extremely short, which is the case for the HORS signature requiring only a single hash function computation. Hmm, this is getting a bit involved, I thought this should sound better than relying on Leashes which have strong assumptions. The authentication on message M_2 ensures to the initiator that the response indeed comes from the correct responder. In the general case, we use the same digital signature for authentication, but if the two nodes share a secret key, we can also use a message authentication code for this purpose, for example HMAC [4]. Similarly, the nonce η_2 and the signature on message M_3 ensure to the responder that the initiator is within transmission range if message M_3 arrives after a sufficiently short delay. Maybe we should write this more concisely. The initial message M_1 is signed to prevent denial-of-service attacks ... need more here, the problem is that verifying that signature will result in a long delay. What about the following idea: the responder's reply is authenticated with a random key, and only if the signature on M_1 is correct, the responder then sends out the signed key. Since we only need authentication and not non-repudiation on this message, this will suffice. In addition, we could use a regular digital signature for this, since the random keys and signatures can be computed off-line.

If wormhole attacks are considered a possible threat, we build our secure Neighbor Detection protocol above a mechanism, such as packet leashes [17], which prevent wormholes between legitimate nodes.

To prevent a node from deriving a well-formed Neighbor Reply based on the Neighbor Reply from another node, we include a nonce η in each New Neighbor Solicitation, and require the Neighbor Reply to include the hash of the nonce and the source address.

$$\begin{aligned}
S: & \quad \eta_1 \xleftarrow{R} \{0, 1\}^\ell \\
& \quad M_1 = \langle \text{NEIGHBOR SOLICITATION}, S, \eta_1 \rangle \\
& \quad \Sigma_{M_1} = \text{Sign}(H(M_1)) \\
S \rightarrow *: & \quad \langle M_1, \Sigma_{M_1} \rangle \\
R: & \quad \eta_2 \xleftarrow{R} \{0, 1\}^{(\ell)} \\
& \quad M_2 = \langle \text{NEIGHBOR REPLY}, S, R, \eta_1, \eta_2 \rangle \\
& \quad \Sigma_{M_2} = \text{Sign}(H(M_2)) \\
R \rightarrow S: & \quad \langle M_2, \Sigma_{M_2} \rangle \\
S: & \quad M_3 = \langle \text{NEIGHBOR VERIFICATION}, S, R, \eta_1, \eta_2 \rangle \\
& \quad \Sigma_{M_3} = \text{Sign}(H(M_3)) \\
S \rightarrow R: & \quad \langle M_3, \Sigma_{M_3} \rangle
\end{aligned}$$

Figure 3: Neighbor detection between initiator S and responder R .

To prevent forgery of New Neighbor Solicitation and New Neighbor Reply packets, we require some form of authentication. If desired, a packet leash can be added to the New Neighbor Solicitation and New Neighbor Reply packets to prevent wormhole attacks. Finally, we rate-limit New Neighbor Solicitations to prevent an attacker from flooding its neighbors. Figure 3 shows the full protocol.

Integration with an On-Demand Protocol. In an on-demand protocol, neighbor verification is performed during each Route Discovery. As a result, we can defend against New Neighbor Solicitation floods, by relying on the underlying protocol to defend against ROUTE REQUEST floods; a node responds to any New Neighbor Solicitation presented with a valid REQUEST. If desired, REQUEST flood prevention can be achieved through the use of a hash chain, as in Ariadne [18]. Explain more?

When a node A forwards a REQUEST, it includes in that REQUEST a broadcast Neighbor Solicitation. Each node B forwarding that REQUEST returns a Neighbor Reply, and piggybacks on the Neighbor Reply a unicast Neighbor Solicitation for A . If A decides that B is a neighbor based on the wormhole prevention mechanism used, A returns a signed Neighbor Verification that verifies the link from A to B . A also includes in packet a Neighbor Reply to the unicast Neighbor Solicitation sent by B . If B decides that A is a neighbor based on the wormhole prevention mechanism used, B forwards the REQUEST, including the Neighbor Verification for the $A \rightarrow B$ link signed by A , and also including a Neighbor Verification for the $B \rightarrow A$ link signed by itself. B need not return a Neighbor Verification, since A is likely to hear the forwarded REQUEST, which includes the $B \rightarrow A$ Neighbor Verification. Figure 4 shows how B forwards a REQUEST from A .

4.3. Secure Route Delegation

In our ROUTE REQUEST propagation, we want to enable each node to verify that all the secure neighbor detection protocols were performed between any adjacent pair of nodes in the REQUEST, i.e., verify that *both* nodes of each adjacent node pair indeed believes to be a neighbor. We achieve this property through a *Secure Route Delegation* mechanism, which is inspired by the work of Kent et al. in S-BGP [23, 24]. S-BGP uses *Route Attestations* to ensure that each Autonomous System (AS) listed in the BGP AS path is indeed a valid AS. In S-BGP, before sending a route update to its neighbor, the AS signs a route attestation delegating it the right to further propagate the update.

We use this mechanism to enable the nodes to verify that all the secure neighbor detection protocols were executed and that *both*

neighbors believe that they are within transmission range. We describe the protocol based on an example. Consider two neighboring nodes A and B , where A received the current ROUTE REQUEST originating from node S destined for node R with the sequence number id . Node A engages in the secure neighboring detection protocol and finds after the second message that B is indeed within range, so it delegates the ROUTE REQUEST to B as follows:

$$\begin{aligned}
M_A &= \langle \text{ROUTE DELEGATION}, A, B, S, R, id \rangle \\
\Sigma_{M_A} &= \text{Sign}(H(M_A)) \\
A \rightarrow B: & \langle \Sigma_{M_A} \rangle
\end{aligned}$$

Node A does not need to send the message to B , as B can reconstruct all the fields of the message and verify the signature. The ROUTE DELEGATION message can be bundled together with the last message of the secure neighbor detection protocol. If B believes that A is indeed a neighbor within range, B will accept the ROUTE DELEGATION, continue the protocol, and sign another ROUTE DELEGATION with the next neighbor.

4.4. Randomized Message Forwarding

The secure neighbor detection and secure route delegation techniques are not sufficient to thwart the rushing attack, since an adversary can still get an advantage by forwarding ROUTE REQUESTS very rapidly. We use a random selection technique to minimize the chance of a rushing adversary.

In traditional ROUTE REQUEST forwarding, the receiving node immediately forwards the REQUEST and suppresses all subsequent REQUESTS. In our modified flooding, a node first collects a number of REQUESTS, and selects a REQUEST at random to forward.

Explain this in more detail, how many requests to collect, how timeouts work, etc.

4.5. Secure Route Discovery

In this section, we describe our secure route discovery protocol. We use three techniques in concert to prevent the rushing attack: our secure neighbor discovery protocol, our secure route delegation and delegation acceptance protocol, and randomized selection of which ROUTE REQUEST will be forwarded.

The intuition behind Secure Route Discovery is to make the forwarding of REQUEST packets less predictable by buffering the first n REQUESTS received, then randomly choosing one of those REQUESTS. However, we need to prevent an attacker from filling too many of these n REQUESTS, since otherwise the attacker could simply rush n copies of a REQUEST, rather than a single REQUEST, and our scheme would once again be vulnerable to the rushing attack.

To limit the number of REQUESTS that traverse an attacker, we exploit the fact that legitimate nodes forward only one REQUEST in any Discovery. First, we require that each REQUEST carry a list of nodes traversed by this REQUEST. Second, we require a bidirectional Neighbor Verification for each link represented by this list of nodes, for a total of two signed Neighbor Verifications per hop. Third, to authenticate the node list, we require each node to authenticate the REQUEST it forwards, though it can piggyback this authentication together with the Neighbor Verification that it signs. Finally, we require buffered REQUESTS be duplicate-suppression-unique: that is, if the route record of any two REQUESTS contain any node A , the route prefix leading up to (and including) A must be the same. These three requirements constrain an attacker to the extent that an attacker that has compromised m nodes can rush at most m REQUESTS.

To prevent replay of old Neighbor Verification messages, each message is tied to a specific Route Discovery. Specifically, when a node S sends a Neighbor Verification for the link from S to R , S signs not just S and R (as in Figure 3), but also ties a unique Route

$$\begin{aligned}
A : & \quad \eta_A \xleftarrow{R} \{0,1\}^\ell \\
& \quad M_{1a} = \langle \text{ROUTE REQUEST}, id, \dots \rangle \\
& \quad M_{1b} = \langle \text{NEIGHBOR SOLICITATION}, A, \eta_A \rangle \\
& \quad \Sigma_{M_1} = \text{Sign}(H(M_{1a} \parallel M_{1b})) \\
A \rightarrow * : & \quad \langle M_{1a}, M_{1b}, \Sigma_{M_1} \rangle \\
B : & \quad \eta_B \xleftarrow{R} \{0,1\}^\ell \\
& \quad M_{2a} = \langle \text{NEIGHBOR REPLY}, A, B, \eta_A, \eta_B \rangle \\
& \quad \Sigma_{M_2} = \text{Sign}(H(M_{2a})) \\
B \rightarrow A : & \quad \langle M_{2a}, M_{2b}, \Sigma_{M_2} \rangle \\
A : & \quad M_{3a} = \langle \text{NEIGHBOR VERIFICATION}, A, B, \eta_A, \eta_B \rangle \\
& \quad \Sigma_{M_{3a}} = \text{Sign}(H(M_{3a})) \\
& \quad M_{3b} = \langle \text{ROUTE DELEGATION}, A, B, S, R, id \rangle \\
& \quad \Sigma_{M_{3b}} = \text{Sign}(H(M_{3b})) \\
A \rightarrow B : & \quad \langle M_{3a}, \Sigma_{M_{3a}}, M_{3b}, \Sigma_{M_{3b}} \rangle \\
B : & \quad \eta'_B \xleftarrow{R} \{0,1\}^\ell \\
& \quad M_{4a} = \langle \text{ROUTE REQUEST}, id, \dots, \Sigma_{M_{3b}}, \Sigma_{M_{4a}} \dots \rangle \\
& \quad M_{4b} = \langle \text{NEIGHBOR SOLICITATION}, B, \eta'_B \rangle \\
& \quad \Sigma_{M_4} = \text{Sign}(H(M_{4a}) \parallel H(M_{4b})) \\
B \rightarrow * : & \quad \langle M_{4a}, M_{4b}, \Sigma_{M_4} \rangle
\end{aligned}$$

Figure 4: *B forwarding the REQUEST from A. Σ_{M_2} can be generated using a shared key, if available. The ROUTE REQUEST in M_{4a} includes the bidirectional Neighbor Verification messages M_{3a} and M_{4c} , together with the necessary authenticators ($H(M_{3b})$ and Σ_{M_3}). The use of $H(M_{3b})$ in Σ_{M_3} allows the verification of M_{3a} without needing M_{3b} , which decreases the overhead caused by the REQUEST packet. The same technique is used in creating Σ_{M_4} .*

Discovery identifier to the Neighbor Verification. For example, in AODV, the RREQ ID and Originator IP Address in an RREQ form a unique identifier; in DSR, the Target Address and Identifier fields from a ROUTE REQUEST, together with the IP Source Address, form a unique identifier. To address wraparound in these Identifier fields, if the nodes in the network have very loosely synchronized clocks (within a few days), the node can include a timeout in addition to this unique identifier. If network nodes have more tightly synchronized clocks (within a few seconds), the node can include a timeout in place of any unique identifier.

In some areas of some networks, a node will not have n distinct paths to the source of the REQUEST. To enable the Discovery of routes to or through such nodes, we allow a node to forward a REQUEST after some time, even if it has not yet received n REQUESTS. In certain cases, however, a fixed timeout allows an attacker to prevent the discovery of a correct route. One way to avoid such an attack is to choose a random timeout between t_{\min} and t_{\max} . Alternatively, we can prefer early release when a node has buffered more REQUESTS, for example by choosing a random timeout between $t_{\min} + (n - j)t_{\text{add}}$ and $t_{\max} + (n - j)t_{\text{add}}$, where j is the number of REQUESTS buffered so far. Choosing a timeout when location information is available can provide better properties. If the initiator of each REQUEST includes a timestamp t and its location, intermediate nodes can choose a timeout of $t + \text{fixed timeout} + \text{propagation speed} \cdot \text{distance to initiator}$. After a node chooses a timeout, either randomly or based on optional location information, the node randomly chooses one received REQUEST for forwarding.

We implement two additional security optimizations to this basic scheme. In general, these optimizations are based on using the property of nonrepudiation to spread information about malicious

nodes. First, we require that each REQUEST be signed by the forwarding node. A node detecting an attacker forwarding more than one REQUEST can expose the attacker by flooding the two REQUESTS. Second, if location information is available, and used for example to implement geographic packet leashes, an attacker claiming to be in two places at the same time can be blacklisted in the same way. For example, if each REQUEST includes in the node list location information and time information for each forwarding node, a node can keep a database of previous location information, and find two location claims that significantly exceed the maximum speed achievable by legitimate nodes. In particular, if location information is accurate to δ , and time information is consistent to Δ , and maximum speed is v , then two locations claimed t time apart is maliciously claimed if the distance between the two locations is greater than $2\delta + v(t + 2\Delta)$. Our blacklist mechanisms do not need authentication, since the nonrepudiation of contradicting information can be verified by any nodes. We route blacklist information by flooding: contradictory information is rebroadcast by any node that verifies the nonrepudiation and did not have this malicious node on its blacklist. This approach is similar to the blacklist mechanism used by Ariadne [18].

4.6. Integrating Secure Route Discovery with DSR

To integrate rushing prevention with DSR [20] or other secure protocols based on DSR, we limit Route Discovery frequency as in Ariadne [18]. Each time a node forwards a ROUTE REQUEST, it first performs a Secure Neighbor Detection exchange with the previous hop. When it forwards the REQUEST, it includes in the REQUEST a bidirectional Neighbor Verification for the previous hop.

As in DSR, the target of a Route Discovery returns a ROUTE REPLY for each distinct ROUTE REQUEST it receives. Each such ROUTE REPLY is sent with a source route selected by reversing the route in the ROUTE REQUEST. This route is likely to work if there are no attackers on the route, since Neighbor Detection only finds bidirectional neighbors.

4.7. Integrating Secure Route Discovery with AODV

In AODV [35], as well as other secure protocols based on AODV [47, 6, 41], Route Request (RREQ) packets do not carry a node list. However, in order to filter excessive malicious RREQs, we require each RREQ to carry a node list. Instead of forwarding the first RREQ received, nodes using our Secure Route Discovery randomly select one of the first n RREQs it receives and treats it as the RREQ to forward. More specifically, it places the initiator of the Route Discovery in its routing table using the previous hop of the RREQ selected as the next-hop destination. It then appends its address and authentication information to the node list, and forwards it as in DSR.

Since AODV is a distance-vector protocol, it cannot make use of multiple routes. As a result, the target of a Route Discovery also waits for n RREQ packets before returning a single RREP. The target signs the RREP, and includes in the RREP neighbor authentication for each hop in the chosen path. This authentication allows nodes forwarding the RREP to authenticate the entire path back to the source of the RREP. Each node authenticating this information establishes a route back to the source of the RREP (the target of the RREQ). When this RREP reaches the destination, it will have established a bidirectional route between the initiator and target of the Route Discovery.

Because AODV does not support multiple routes, the security properties of AODV using Secure Neighbor Discovery will be somewhat worse than the properties of DSR using Secure Neighbor Discovery.

4.8. Integrating Secure Route Discovery with Secure Ad Hoc Network Routing Protocols

When using our rushing attack prevention together with a secure on-demand routing protocol, a node can first attempt Route Discovery using that secure protocol. If a rushing attacker prevents the discovery of any working routes, the node can then set a flag indicating that it wants to use routing attack prevention, though it must also authenticate that flag to prevent modification. This approach is similar to the principle of *expanding ring search*: first, a node uses a cheaper, but sometimes unsuccessful, search. The node only uses a more expensive search when the cheaper search does not find a route. This optimization provides benefits in two cases: first, when there are no rushing attackers, existing secure routing protocols should be able to find a route. Secondly, a rushing attacker does not have any advantage in one- and two-hop routes.

5. EVALUATION

To evaluate our techniques, we analyzed the cost and effectiveness through simulation and analysis. Our simulation was designed to show the cost of our techniques in a non-adversarial environment, whereas our analytical evaluation shows provable bounds on the extent to which an attacker can disrupt a protocol using our techniques.

5.1. Simulation Evaluation

To evaluate the overhead of using our secure neighbor discovery mechanism in a non-adversarial environment, we simulated our scheme using the *ns-2* simulator, using Ariadne [18] as our underlying routing protocol. We call this modified protocol RAP (Rushing Attack Prevention). We did not implement the optimizations described in Section 4.8, because our simulations did not include an attacker, so our results would be equivalent to just using Ariadne. We used the original Ariadne source code [31], and modified it to use digital signatures based on HORS and geographical leases for wormhole protection [15]. We compared our results with Ariadne and DSR in order to determine the added costs of RAP when there are no attackers. However, when a rushing attacker is present, existing on-demand ad hoc network routing protocol would in general be unable to deliver packets over paths longer than two hops (Section 2). RAP, on the other hand, would be able to discover working paths much of the time, and as a result, would generally outperform existing on-demand routing protocols.

We chose HORS as our broadcast signature, using a time interval of 5 seconds and allowing each node to authenticate up to 20 messages per time interval. We assumed a time synchronization error of 1 second, and used 180 byte signatures. As a result, each public key is 78380 bytes, and each node has an amortized workload of 156760 hash operations per second at each node for generating signatures, as well as verifying all signatures from all nodes. (This level is well within the capability of modern PDAs, and represents around 10% CPU utilization on modern workstations). Our parameters were chosen to provide an 80 bit security level; that is, an attacker must guess 2^{80} signatures to forge one signature in expectation. When signatures were needed at a faster rate than permitted by HORS, we used a multi-signature scheme based on Merkle hash trees [30]. We simulated packet leases based on optional location information, and waited for 2 REQUEST packets, or a 0.2 seconds fixed timeout plus the distance to the initiator times a propagation speed of 1500 meters per second.

Because a square area is more likely to support multiple routes between a source and a destination, our simulations used 100 nodes

in a $1000\text{ m} \times 1000\text{ m}$ space moving according to the *random waypoint model* [21]. In this model, each node is randomly placed; at the beginning of the simulation, it waits for a *pause time*, then chooses a velocity uniformly between 0 and 20 meters per second. It then proceeds to a random location at that velocity, and upon arriving, waits for the pause time and repeats. We simulated pause times of 0, 30, 60, 120, 300, 600, and 900 seconds.

We chose a workload of 5 flows, each producing 4 packets per second, using 64-byte packets. This workload was sufficient to cause significant congestion with our scheme, even though normal ad hoc network routing protocols can deliver four or more times the load at lower loss rate; however, secure neighbor discovery incurs significantly higher overhead due to the four-way handshake and speed-of-light delays associated with it. We simulated a link-layer data rate of 2 Mbps.

RAP has significantly worse performance than both Ariadne and DSR because of the added load of the Secure Neighbor Discovery. Figure 5(a) shows the Packet Delivery Ratio of the three protocols. DSR delivers between 99.8% and 100% of offered traffic. Ariadne delivers between 95.0% and 100% of offered traffic; a significant improvement over previous simulation results [18]. This suggests that previous simulations used too high a traffic load to fairly evaluate Ariadne in the absence of congestion. Even with this light traffic load, RAP was able to deliver just 7.6% to 47.7% of offered load. This performance is primarily due to congestion. At higher movement speeds (lower pause time), the lower packet delivery ratio is caused by an even higher packet overhead, which results from the on-demand nature of the protocol. We also simulated RAP carrying a lower load of just one flow. At higher pause times, Ariadne with RAP has sufficiently low overhead to deliver between 73.7% and 74.5% of traffic. Even with these pause times, 92.1% of drops were due to MAC-layer congestion, compared to just 4.15% due to the node's inability to find a route. This MAC-layer congestion severely hampers our protocol's ability to deliver application-layer packets.

Figure 5(b) shows the median latency of delivered packets. DSR and Ariadne appear to have zero mean latency, since their median latencies of 4.3ms and 3.8ms respectively are significantly lower than the 1050ms median latency of RAP. Two factors contribute to the higher latency of RAP: first, congestion increases the time each node must wait to acquire the medium, and second, if a node receives just one ROUTE REQUEST packet from a Route Discovery, it waits a significant amount of time before forwarding that REQUEST in an attempt to collect enough REQUESTs and choose one at random.

Figures 5(c) and 5(d) show the Packet Overhead and Byte Overhead of the three protocols. At higher pause times, RAP has more than five times as much overhead when it uses five flows. This indicates that the congestion caused by the protocol significantly reduces the usefulness of the routing protocol packets. When congestion is not an issue, we actually expect that overhead should be less than a factor of five, because nodes can cache information they overhear, thus improving efficiency.

Our performance evaluation shows that in non-adversarial environments, RAP adds significant costs relative to other secure routing protocols. Many of these costs are due to the congestion created at lower bit rates. However, RAP is designed to be used only when necessary (Section 4.8), so these higher costs are only incurred when the underlying protocol is otherwise unable to discover a working route. Specifically, RAP incurs *no cost* until the underlying protocol is completely prevented from finding a working route. It then allows that protocol to use a higher cost approach to successfully deliver packets even against a rushing attacker. In the

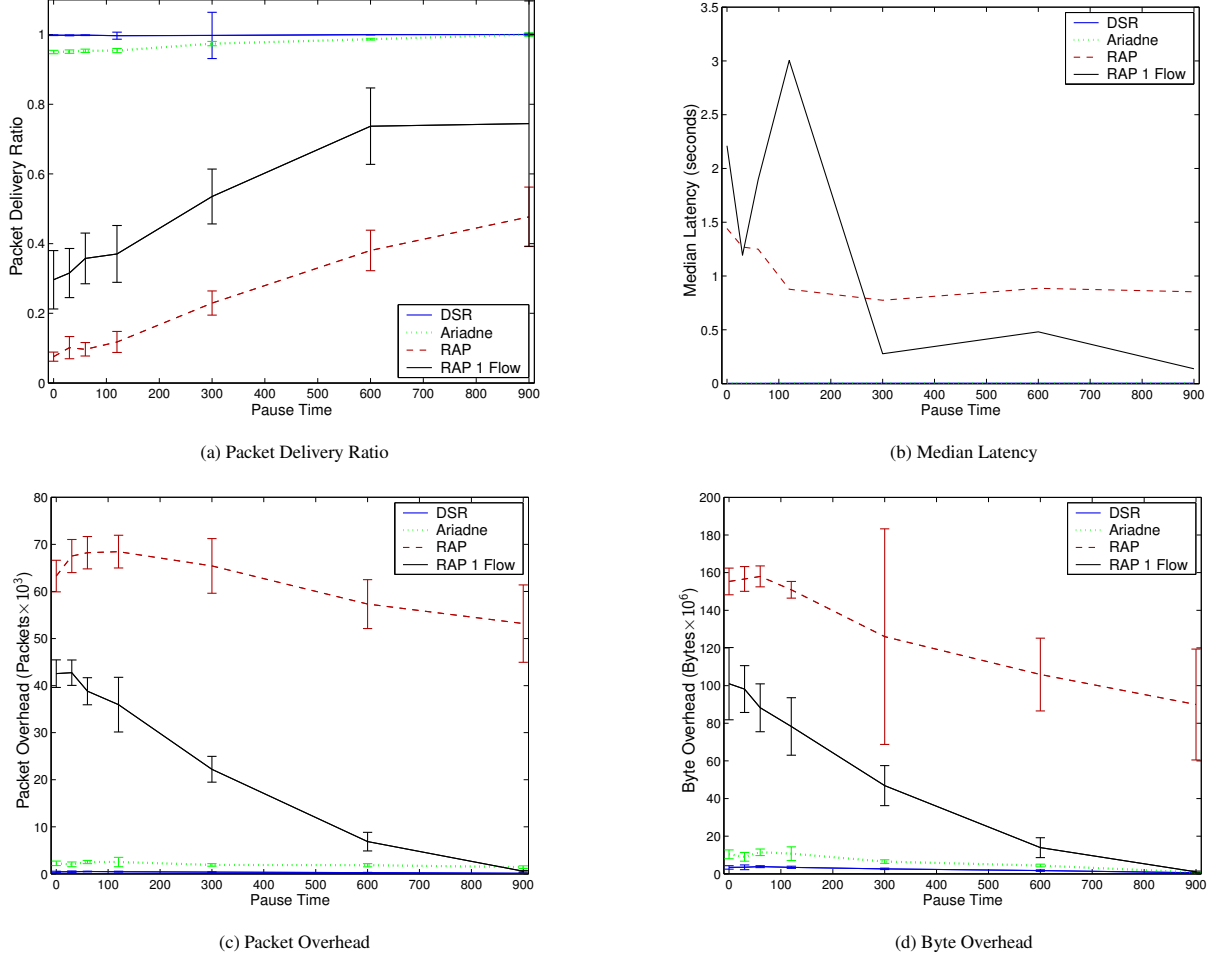


Figure 5: Unoptimized RAP performance evaluation results in non-adversarial environment. Optimized RAP would have same results as Ariadne, except that it would perform better when under attack. Under attack, optimized RAP and Ariadne would perform identically for one- and two-hop routes, but in finding longer routes, RAP should significantly outperform Ariadne, since RAP finds working routes with moderate probability, but Ariadne and DSR can never find routes. “RAP 1 Flow” refers to RAP with the lighter communications pattern of one CBR source. Results based on averages over 50 simulation runs; the error bars represent the 95% confidence interval of the mean.

next section, we show how RAP performs under a rushing attack, in which DSR and Ariadne would be unable to find routes containing more than three nodes (two hops).

5.2. Security Analysis

This section discusses the security properties achieved with RAP when n distinct routes (both legitimate and attacking) exist between the originator and each other node in the network. (As in Section 4.5, two routes are considered distinct if they end in different nodes.) Since routes are required to end in different nodes, an attacker with access to the keys of m compromised nodes can generate at most m distinct, maliciously injected ROUTE REQUESTS for the purpose of denial-of-service.

To analyze the probability of a node subverting a Route Discovery, we assume that the attacker rushes m distinct REQUESTS to each node in the network. As a result, each node needs only $n - m$ additional distinct REQUESTS. We also suppose that the network topology of these legitimate requests is represented by Figure 6,

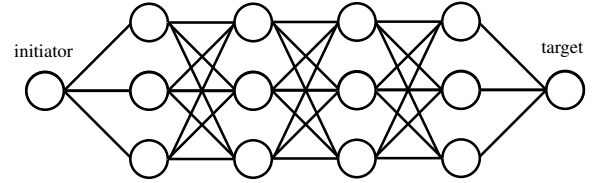


Figure 6: Example network topology used in RAP security analysis.

such that the ℓ hops from the source to the target form a sequence of tiers, such that the $n - m$ neighbors of the source form the first tier, the $n - m$ neighbors of the target form the last tier, and any two adjacent tiers form a complete, bipartite graph.

We denote the probability of successfully finding a route at tier x given y nodes at that tier to be $S_{x,y}$. In particular, we seek the probability $S_{\ell,n-m}$. Since one-hop neighbors cannot be subverted, $S_{1,y} =$

$$\begin{aligned}
S_{x,y} &= \sum_{i=1}^y \left[\binom{y}{i} \left(\frac{m}{n} \right)^{y-i} \left(\frac{n-m}{n} \right)^i \sum_{j=1}^{\min(i,n-m)} S_{x-1,j} p_{n-m-j}(n-m,i) \right] \\
&= \sum_{i=1}^y \left[\binom{y}{i} \left(\frac{m}{n} \right)^{y-i} \left(\frac{n-m}{n} \right)^i \sum_{j=1}^{\min(i,n-m)} \left\{ S_{x-1,j} \binom{n-m}{n-m-j} \sum_{k=0}^j (-1)^k \binom{j}{k} \left(\frac{j-k}{n-m} \right)^i \right\} \right]
\end{aligned}$$

Figure 8: The probability of a successful Route Discovery in a network using RAP

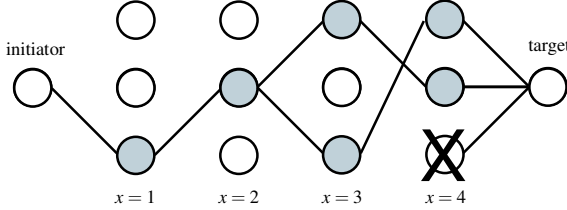


Figure 7: An example of a successful Route Discovery. Each gray node chose a valid REQUEST and belonged to a route for which a REPLY was sent. Each line represents a hop in a path chosen by a legitimate REQUEST; the network topology is shown in Figure 6.

1 for all $y > 0$. At any other level (that is, when $x \neq 1$), the probability that i of the y neighbors will choose one of the m bogus ROUTE REQUESTs is given by the binomial PDF $\binom{y}{i} \left(\frac{m}{n} \right)^{y-i} \left(\frac{n-m}{n} \right)^i$. For example, in Figure 7, at $x = 4$, $y = 3$ nodes received a valid ROUTE REPLY, but only $i = 2$ of them forwarded a valid REQUEST.

Each of the i nodes that do not choose bogus REQUESTs chooses one of the REQUESTs it received. Some of these REQUESTs may overlap; the probability of choosing exactly j distinct previous hops is given by $p_{n-m-j}(n-m, i)$, where $p_{r-j}(r, i)$ is the probability that when i balls are thrown into r boxes, exactly $r - j$ boxes are empty (that is, exactly j boxes are full). The solution to the classical occupancy problem [45] gives $p_{r-j}(r, i) = \binom{r}{r-j} \sum_{k=0}^j (-1)^k \binom{j}{k} \left(\frac{j-k}{r} \right)^i$. For example, in Figure 7, at $x = 4$, $i = 2$ nodes chose $j = 2$ distinct previous hops, and at $x = 3$, $i = 2$ nodes chose $j = 1$ distinct previous hops.

When, at a level $x \neq 1$, i nodes do not choose bogus REQUESTs but instead choose a total of j distinct, legitimate REQUESTs, the probability that the Route Discovery will be successful is $S_{x-1,j}$ by definition. Then $S_{x,y}$ is given by the equation in Figure 5.2. For example, when $n = 6$, $m = 2$ and $\ell = 5$, the probability of a successful Route Discovery is 46%.

We now argue that the case above reflects a worst case analysis by analyzing some potential variations. First, the $n - m$ additional incoming nodes could come from earlier tiers (e.g., tiers with lower x). However, since $S_{x,y}$ is monotone decreasing with increasing x and fixed y , the opportunity to choose nodes from earlier tiers only provides a benefit. Second, there may not be as much overlap between the predecessors of the nodes in a single tier; however, this only reduces the number of collisions at the previous tier. Fewer collisions at the previous tier improves performance, since $S_{x,y}$ is monotone increasing with fixed x and increasing y . Third, an attacker can choose to reduce the number of bogus REQUESTs it sends to each node; this has the effect of reducing m , which again increases the probability of success. A final attack allows a powerful attacker to monitor the REQUESTs forwarded by each node

legitimate node. Some of these legitimate nodes will have randomly chosen REQUESTs that represent compromised routes. The attacker can then attempt to forward such REQUESTs to nodes that did not hear that REQUEST directly from that node. This attack will be prevented by wormhole detection.

As mentioned in Section 4.7, if only one ROUTE REPLY is returned with any discovery, security is somewhat lower. In particular, only one route is returned, and each hop after the first has a $\frac{n-m}{n}$ probability of choosing a nonattacking node under the attacker model used in this section. In a working route, all nodes must forward a nonattacking REQUEST. As a result, the probability of choosing a working route is $\left(\frac{n-m}{n} \right)^\ell$, where ℓ is the number of intermediate nodes (excluding the initiator and target).

This section presented an extremely conservative security analysis. In particular, an attacker as aggressive as the one described here would need to propagate the ROUTE REQUEST from each Route Discovery from many different locations, subjecting it to the intrusion detection mechanism. A real attacker considering the tradeoff between an improved probability of subversion and an increased probability of being caught is unlikely to use such a powerful attack.

6. RELATED WORK

We have already discussed the vulnerability of current secure on-demand ad hoc network routing protocols [6, 41, 18, 33, 47] to the rushing attack in Section 2. Perlman's Flooding NPBR [36] routing protocol for wired networks does not suffer from this attack, since the protocol does not depend on the actual path of the flood for routing; rather, it requires that each packet be flooded through the network.

Other secure routing protocols have been proposed based on periodic (proactive) mechanisms, for wired networks [7, 12, 13, 23, 27, 42, 43] as well as for wireless ad hoc networks [14, 38]. Although these protocols typically are not vulnerable to rushing attacks, such periodic protocols are often less desirable for ad hoc network routing due to their higher overhead and slower adaptivity.

Other areas in secure ad hoc network routing have been explored, such as trust establishment [2, 18, 19, 44], key generation [3], nodes that maliciously do not forward packets [29], and security requirements for forwarding nodes [46]. These areas are beyond the scope of this paper.

Routing protocol intrusion detection has been studied in wired networks as a mechanism for detecting misbehaving routers. Cheung and Levitt [8] and Bradley et al [5] propose intrusion detection techniques for detecting and identifying routers that send bogus routing update messages. In this paper, we describe one invariant of legitimate node behavior, and introduce a distributed mechanism to exclude nodes that have been caught violating that invariant.

7. CONCLUSION

In this paper, we have described the *rushing attack*, a novel and powerful attack against on-demand ad hoc network routing protocols. This attack allows an attacker to mount a denial-of-service attack against *all* previously proposed secure on-demand ad hoc network routing protocols. We have also presented RAP (Rushing Attack Prevention), a new protocol that thwarts the rushing attack.

We found that the widely used duplicate suppression technique makes the rushing attack possible, and we designed a new Route Discovery protocol called RAP that replaces the standard mechanism and thwarts the rushing attack. Our approach is generic, so any protocol that relies on duplicate suppression in Route Discovery can use our results to fend off rushing attacks. More importantly, we demonstrated that there are mechanisms that can defend against the rushing attack, even though all previous attempts at secure on-demand ad hoc network routing protocols have been vulnerable.

When integrated with a secure routing protocol, RAP incurs *no cost* unless the underlying secure protocol cannot find valid routes. When RAP is enabled, it incurs higher overhead than do standard Route Discovery techniques, but it can find usable routes when other protocols cannot, thus allowing successful routing and packet delivery when other protocols may fail entirely. We have also shown that existing on-demand routing protocols can be retrofitted using our technique to resist the rushing attack.

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