Detecting and Avoiding Wormhole Attacks in Wireless Ad Hoc Networks

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ABSTRACT

A particularly severe attack on routing protocols in ad hoc networks is the so-called wormhole attack in which two or more colluding attackers record packets at one location, and tunnel them to another location for replay at that remote location. When this attack targets specifically routing control packets, the nodes that are close to the attackers are shielded from any alternative routes with more than one or two hops to the remote location. All routes are thus directed to the wormhole established by the attackers. In the optimized link state routing protocol, if a wormhole attack is launched during the propagation of link state packets, the wrong link information percolates throughout the network, leading to routing disruption. In this article we devise an efficient method to detect and avoid wormhole attacks in the OLSR protocol. This method first attempts to pinpoint links that may potentially be part of a wormhole tunnel. Then a proper wormhole detection mechanism is applied to suspicious links by means of an exchange of encrypted probing packets between the two supposed neighbors (endpoints of the wormhole). The proposed solution exhibits several advantages, among which are its nonreliance on any time synchronization or location information, and its high detection rate under various scenarios.

INTRODUCTION

Due to the versatile nature of their application domain, mobile ad hoc networks are very likely to often be deployed in hostile environments. Due to numerous constraints such as lack of infrastructure, dynamic topology, and lack of pre-established trust relationships between nodes, most of the envisioned routing protocols for ad hoc networks are vulnerable to a number of disruptive attacks. In this article we focus on the so-called wormhole attack, which is known to be particularly challenging to defend against [1], and has been shown to be potentially damaging to a wide range of ad hoc routing protocols.

In a wormhole attack a hostile node constantly monitors the channel, records packets overheard in its vicinity, and tunnels them to a remotely located colluding node, who will replay them in its floor. When this tunneling particularly targets routing control packets such as HELLO messages and route requests (RREQs), nodes close to the attackers are unable to discover the legitimate routes that originate and end in the vicinity of the two attackers: in the typical wormhole attack scenario, such legitimate routes would span more hops than the one or two hops declared by the wormhole attackers. This severely disrupts the network operation. For example, when used against an on-demand routing protocol, such as Ad Hoc On Demand Vector (AODV) or DSR [2], this attack prevents any node from discovering routes of more than two hops. This can be done by tunneling each RREQ message, originating from a node close to the attacker, directly to the target node of the route request. Periodic protocols such as Optimized Link State Routing (OLSR) and TBRPF [2] are also vulnerable to this attack. For example, OLSR uses HELLO packets for neighbor discovery. Considering the scenario in Fig. 1, if the two colluding attackers X and Y tunnel HELLO packets transmitted by B to A in OLSR or TBRPF and B to A in OLSR or TBRPF and B to A in OLSR or TBRPF, A and B will believe that they are direct neighbors and select each other to route all ensuing data packets. The result of this is that a large number of data packets are directed to the wormhole, with ultimately all the side effects that this may induce such as congestion, packet loss, eavesdropping, spoofing, and so on.

In this article we introduce an efficient method to detect and prevent wormhole attacks in OLSR. Our solution first tries to pinpoint links that may possibly belong to wormhole tunnels, and then applies an appropriate wormhole detection mechanism by means of an exchange of encrypted probing packets between the two supposed neighbors (endpoints of the wormhole). The proposed solution exhibits several advantages, among which are its nonreliance on any time synchronization or location information, and its high detection rate under various scenarios.
packets between the two supposed neighbors (endpoints of the wormhole) to distinguish between wormhole links and other legitimate ones. Our solution has several advantages among which is its nonreliance on any time synchronization or location information.

The remainder of this article is organized as follows. We present some related work on the wormhole attack problem in ad hoc networks. We describe the features of the wormhole attack and how it works in OLSR. We present our method to detect suspicious links and wormhole tunnels in OLSR. Some simulation results are given to characterize the performance of our proposed method. We finally draw our conclusions.

**RELATED WORK**

Several approaches have been developed to defend against wormhole attacks in mobile ad hoc networks. In [1] packet leashes are used to protect reactive routing protocols against wormhole attacks. A leash is defined as any information appended to a packet to restrict the maximum transmission distance of the packet. Two kinds of leashes have been proposed: *geographical* and *temporal*. In the geographical leash, the sender appends its location and the sending time to a packet. Based on this information, the receiving node computes an upper bound on the distance to the sender. This solution in fact requires location information and coarse synchronization of all nodes in the network. In the temporal leash, the sender appends the sending time to the packet, and the receiving node computes a traveling distance of that packet assuming propagation at the speed of light, and using the difference between the packet sending time and packet receiving time. This solution requires fine-grained synchronization among all nodes. In [3] directional antennas are used to prevent against wormhole attacks. Each node in the network shares a secret key with every other node and broadcasts HELLO messages to discover its neighbors using directional antennas in each direction.

The SECTOR protocol [4] presents a countermeasure against wormhole attacks by allowing nodes to prove their encounters with other nodes. However, several hypotheses are needed for this protocol to work correctly. Among these are the necessity for coarse synchronization, the ability of nodes to measure their local timing with nanosecond precision, the pre-establishment of security associations between each pair of nodes, and the presence of a central authority that controls the network membership.

So-called disjoint-path-based approaches have been adopted recently. In [5] a statistical approach based on multipath routing is proposed. This approach uses the relative frequency of each link when discovering routes within the network. The main idea beneath this approach resides in the fact that the relative frequency of a link which is part of a wormhole tunnel is much higher than other normal links.

In [6] the proposed DelPHI protocol allows a sender to observe the delays associated with the different paths to a receiver. Therefore, a sender can check whether there are any malicious nodes sitting along its paths to a receiver trying to launch wormhole attacks. The obtained delays and hop count information of some disjoint paths are used to decide whether a certain path among these disjoint paths is under a wormhole attack.

There are also some other methods proposed in the literature [7–9] to defend against wormhole attacks. However, most of these methods require fine-grained time synchronization between nodes in the network or special hardware to prevent against the wormhole attack.

**ATTACK MODEL**

**DESCRIPTION OF WORMHOLE ATTACKS**

A wormhole attack is composed of two attackers and a wormhole tunnel. To establish a wormhole attack, attackers create a direct link, referred to as a *wormhole tunnel*, between them. Wormhole tunnels can be established by means of a wired link, a high-quality wireless out-of-band link, or a logical link via packet encapsulation. After building a wormhole tunnel, one attacker receives and copies packets from its neighbors and forwards them to the other colluding attacker through the wormhole tunnel. This latter node receives these tunneled packets and replays them into the network in its vicinity. In a wormhole attack using a wired link or a high-quality wireless out-of-band link, attackers are directly linked to each other, so they can communicate swiftly. However, they need special hardware to support such communication. On the other hand, a wormhole using packet encapsulation is relatively much slower, but it can be launched easily since it does not need any special hardware or special routing protocols.

**WORMHOLE ATTACK IN OLSR**

Since a wormhole attack can heavily affect topology construction, it may be lethal to many ad hoc routing protocols, especially proactive routing protocols such as OLSR, which periodically exchange control packets for neighbor discovery and topology construction. Figure 1 depicts an ad hoc network including a wormhole tunnel. When node A broadcasts its HELLO message,
node X (an attacker) copies this HELLO message and tunnels it to node Y (the colluding attacker) through the constructed wormhole. Y receives A’s HELLO message and replays it in its floor. When node B receives the replayed HELLO message, B deems node A to be its one-hop neighbor. Following a similar procedure, node A may be brought to assume node B to be its one-hop neighbor. After a certain time, a symmetric link can be established between A and B according to the OLSR mechanism. Once the symmetric link is established, A and B are very likely to choose each other as multi-point relays (MPRs), which then leads to an exchange of some topology control (TC) messages and data packets through the wormhole tunnel. In our example of Fig. 1, B can reach A’s one-hop neighbors, which are part of B’s two-hop neighbors, only through A. Therefore, B has to select A as its MPR to reach A’s one-hop neighbors. Although there are other routes to A and A’s one-hop neighbors, because of the wormhole, other routes are certainly more than two hops long. Moreover, in OLSR only MPR nodes can forward TC messages, so selecting MPRs that forward flawed topology information will result in the spread of incorrect topology information throughout the network. This leads to routing disruption and ultimately results in significant performance degradation of the ad hoc network as a whole.

**DETECTING WORMHOLE ATTACKS**

In this section we describe our proposed method for detecting and preventing wormhole attacks against OLSR. In our approach the nodes first try to detect links suspected to be part of a wormhole. They then try to ascertain such information through a judicious exchange of newly defined control packets.

**DETECTING SUSPICIOUS LINKS**

In OLSR each node periodically broadcasts a HELLO message to discover its own one-hop neighbors. Upon reception of a HELLO message, a node regards the originator of the HELLO message as a neighbor. However, in a wormhole attack this HELLO message can be replayed from afar (more than one hop away). While this operation does not compromise any nodes, it can give wrong information to the underlying routing protocol and may ultimately cause its failure in finding adequate routes. Two nodes are regarded as neighbors if and only if they are within transmission range of each other.

In our proposed approach we first detect network links with high probability to be involved in a wormhole attack. One commonly accepted and invoked representative feature of wormhole attacks consists of relatively longer packet latency than the normal wireless propagation latency on a single hop. This is typically because, in a wormhole attack, many other multipath routes are channeled to the wormhole. The load on the single route increases, leading to typically longer queuing delays in the wormhole. Nevertheless, this is not a sufficient condition for the existence of a wormhole, because packet transmission is affected by various factors like congestion and intranodal processing. So delay alone may lead to false identification of wormholes. Instead, in our approach links that experience long delays are treated as suspicious links. As such, wormhole verification must be performed only on such suspicious links.

To infer suspicious links, we define two new control packets for the OLSR protocol: HELLO\textsubscript{req} and HELLO\textsubscript{rep}. The HELLO\textsubscript{req} message supersedes the standard HELLO message in OLSR, and depending on the option used, it can bear one of two meanings. In the standard option it functions as the original message. In another option a node uses the HELLO message to request an explicit reply from its neighbors. In this option, upon receiving a HELLO\textsubscript{req} message, the neighbors must respond with a HELLO\textsubscript{rep} message. HELLO\textsubscript{req} and HELLO\textsubscript{rep} have exactly the same format, and the three packet types (standard HELLO, HELLO\textsubscript{req} and HELLO\textsubscript{rep}) are distinguished by using two of the unused bits in the original message.

After each \( N \) standard HELLO message transmissions, a node must send one HELLO\textsubscript{req} message (requesting thereby explicit HELLO replies from its neighbors) and set an expiry \textit{timeout} for the transmitted HELLO\textsubscript{rep}. The value of \( N \) can be adjusted according to the desired security level. If the application needs a high security level and has to detect launched attackers rapidly, \( N \) should be set to an adequately small value.

When a node receives a HELLO\textsubscript{req}, it records the sender’s address \( i \) and the time \( \Delta_i \) left until it is scheduled to send its next HELLO message. The default HELLO message transmission interval is 2 s in OLSR [2]. To avoid overloading the network with too many HELLO replies, a receiver delays the replies of multiple requests until it is scheduled to send its normal HELLO message, and piggybacks the replies to this HELLO message. For each piggybacked reply, the node attaches the recorded address of the sender of the corresponding HELLO\textsubscript{req} and the respective values of \( \Delta_i \). Figure 2 shows an example of a timing diagram where a HELLO\textsubscript{req} aggregates replies of three previously received HELLO\textsubscript{req} messages.

When a node receives a HELLO\textsubscript{rep}, it checks whether this HELLO\textsubscript{rep} contains information related to any of its outstanding requests. If there is no information about its previous requests, the node treats the received HELLO\textsubscript{rep} as any normal HELLO message. Otherwise, the node checks the HELLO\textsubscript{rep}’s arrival time to see whether the HELLO\textsubscript{rep} has arrived within its scheduled timeout interval while taking into account the corresponding delay \( \Delta_i \) incurred at the receiver. If HELLO\textsubscript{rep} arrives within its timeout, the originator ranks the link between itself and the node that sent HELLO\textsubscript{rep} as proven safe. In this case the originator updates its data on the neighbor relationship with that node and neighbors advertisement from that node (see [2] for the details). If HELLO\textsubscript{rep} does not arrive within its scheduled timeout, the originator ranks the link between itself and the node that has sent the HELLO\textsubscript{rep} as suspicious and stops communicating with that node until the end of the wormhole verification procedure.
After detecting suspicious links, the originator of HELLOreq performs a verification procedure for each suspicious link to check whether there is any wormhole tunnel sitting along the path between itself and the other endpoint of the suspicious links. For this purpose, two new messages are added to the protocol. To detect the wormhole tunnel, the node sends a Probing packet to all of its suspect nodes. When a node receives the Probing packet, it replies with an ACKprob message to the originator of the Probing packet after stopping all transmissions of data packets. Let a Probing packet be sent by a node i to query a node j about its own wormhole status reputation. Node j replies with an ACKprob packet where it piggybacks its own opinion about the status of node i. The reputation state of a node that has been inferred in the previous exchange of HELLOreq and HELLOrep procedure can be either “proved” or “suspicious” depending on the conclusions derived from the suspicious link detection procedure. The ACKprob also contains the processing taken by the receiver of the Probing packet until the time it responded with the ACKprob. This timing information is used to tune an accurate timeout. If the node that receives a Probing packet does not have any information about the state of the source node, it omits sending the ACKprob and starts collecting the desired information by means of HELLOreq and HELLOrep exchanges. When the originator of the Probing packet receives HELLOreq instead of ACKprob, it immediately sends a HELLOrep and initializes a new timeout only for this node. The timeout of other nodes is not changed. When the node receives HELLOrep, it decides the state of the node that sends HELLOrep and sends this information to the originator of the Probing packet through ACKprob. If a node has to send both a Probing packet and ACKprob, each packet can piggyback another packet.

Figure 3 shows an example of a timing diagram of the exchange of these messages. To ensure the security of exchanging a Probing packet and ACKprob, end-to-end authentication is needed as in [10]. A sender chooses a large random number, sufficiently large that an attacker cannot guess, and concatenates it to the Probing packet. After that, the sender hashes the Probing packet and encrypts that message. If nodes use digital signatures, the sender sends the encrypted message with its certificate. Otherwise, if two nodes share a secret key, we can use symmetric key cryptography instead. When the node receives an encrypted Probing packet, first it decrypts that packet and then verifies the sender’s identity. If the authentication is successful, the node builds an ACKprob that contains the state of the sender and the large random number that is chosen by the sender. In the same way the node hashes the ACKprob and encrypts it before sending it. After its reception, the sender verifies the validity of the ACKprob message before using the information it contains.

Once again, the originator of the Probing packet checks whether the ACKprob arrived within the required timeout. Similar to the HELLOreq and HELLOrep procedure, the originator also decides in this exchange about possible suspicious links. To decide whether a suspicious link is traversing a wormhole tunnel, the node compares its evaluation of the reputation of the other endpoint of the suspicious link with the other node’s evaluation of its own reputation status:

(Proved, Proved): If the result of the reputation of the remote node is proved and the contents of the encrypted ACKprob is proved, the originator concludes that the link between itself and the suspicious node does not contain a wormhole tunnel. The originator maintains the neighbor relationship with this node and accepts information from that node.
If one of the two nodes judges the remote node or the content of ACK as suspicious, the originator concludes that the link is still suspicious. In this case the originator restarts communication with that node after a randomly chosen time. When this time expires, the originator proceeds again with the exchange of Probing and ACK Packets. If the result of this exchange leads to the conclusion of at least one suspicious state, the originator treats this link as a wormhole tunnel.

(Suspicous, Suspicious): If the reputation of the remote node and the contents of the ACK are suspicious for both nodes, the originator concludes that the link contains a wormhole tunnel. As a result, the originator removes that node from its one-hop neighbors list and the two-hop neighbors which are one-hop neighbors to that node. If the suspected node has been chosen as an MPR, the originator moves it to a list of forced non-MPR nodes. The originator does not use that link, and packets arriving via that link are dropped until the next HELLO exchange procedure. If the originator has packets to send to the suspicious node, it has to find another path to reach that node excluding the wormhole link. If there is no other path to that node, the originator waits for the next HELLO exchange procedure to discover alternate paths.

Timeouts
The value of the timeout has to be calculated carefully in order to avoid false decisions. If the timeout value is set too small, legitimate nodes can be mistakenly suspected. On the other hand, if the timeout is set to a very large value, it becomes hard to detect almost any wormhole attack. The timeout setting is related to whether it can distinguish the normal wireless transmission range of a single hop. Timeout can be then defined as follows:

\[
\text{Timeout} = \frac{2R}{V} + T_{\text{proc}},
\]

where \( R \) denotes the maximum transmission range of each node or radio coverage, \( V \) is the propagation speed of the wireless signal (e.g., light speed \( C \)). In our solution, if a link is regarded as suspicious, the link is given another chance to prove its legitimacy rather than being subject to immediate coercive measures. The parameter \( T_{\text{proc}} \) denotes the packet processing time and queuing delays within nodes. Usually, \( T_{\text{proc}} \) is hard to calculate by formulation as it heavily relies on topology, the amount of traffic sent/received, and link conditions (with many collisions or not). In our solution a sender uses an approximation of a receiver’s \( T_{\text{proc}} \) because it is not used for any authentication in the HELLO-HELLO exchange procedure. When the originator sends normal HELLO messages and HELLO messages, it records the difference between packet scheduling time and real transmission time. An average of the latest three records is calculated and is used as \( T_{\text{proc}} \) in the HELLO-HELLO exchange procedure. However, an approximation of \( T_{\text{proc}} \) is not needed in the Probing-ACK exchange procedure due to the used end-to-end authentication. Therefore, the sender uses \( T_{\text{proc}} \) from the receiver, the difference between the Probing packet receiving time, and the ACK sending time to decide whether there is a wormhole link or not.

Performance Evaluation
In this section we evaluate the performance of our scheme using the ns-2 simulator. We generated a number of random topologies with \( M \) nodes over a square field, where \( M \) ranges from 10 to 50. The square field size is varied from 300 \times 300 m to 1500 \times 1500 m depending on network size (i.e., number of nodes). The maximum transmission range of each node is set to 250 m. The malicious node pair is selected randomly among the nodes in the formed network. To prevent statistical biases, the presented results are the average of 100 simulation runs. Every node, including the malicious nodes, and control messages such as HELLO or TC messages follow the default settings in the specifications of the OLSR protocol [2].

Figure 4 shows the wormhole link detection rate as a function of the tunnel length for different network sizes. Tunnel length refers to the number of hops between the malicious nodes. The HELLO emission interval is equal to 5 (which means that after sending five normal HELLOs, a HELLO emission is sent), and the duration of the wormhole attack is set to 30 s. We define a wormhole link detection rate as the proportion of the number of detected links that contain wormhole tunnels to all links that contain wormhole tunnels. The results show that wormholes are detected more in the configuration where this attack is launched over a longer hop count. This result is quite obvious, since through a wormhole tunnel packets are encapsulated and decapsulated repeatedly, which leads to more delayed transmissions. In the case of less than three hops, the detection rate is relatively low.
This can be explained by the effect of an overestimated $T_{proc}$. In fact, when the sender has many packets to send, $T_{proc}$ can erroneously be set to a large value. Therefore, as the sender's $T_{proc}$ can be overestimated, some wormhole attacks go undetected. However, we can notice that this overestimated $T_{proc}$ does not affect the detection rate of wormhole attacks over a path with a length exceeding four hops. We conclude here that the number of nodes constructing the wormhole tunnel more or less affects its detection.

Figure 5 shows results on detection accuracy. Detection accuracy is measured as the ratio of links that effectively contain wormhole tunnels to the links that are judged suspicious by our solution. The results show that detection accuracy depends on the correlation between the number of nodes and the tunnel length. In a network of 15 nodes, the detection accuracy rarely decreases as the tunnel length increases. However, in larger networks (e.g., 30 and 50 nodes), the detection accuracy decreases dramatically as the tunnel length increases. This can be explained by the number of neighbors that can be selected to form wormhole tunnels by malicious nodes. When the number of nodes in the network is equal to 15, the number of any node's neighbors is more likely to be small; as the tunnel length increases, it becomes more obvious to find another route similar to that of the detected wormhole tunnel. However, if the number of nodes in the network becomes larger, malicious nodes are more likely to have many neighbors even though they are far away from each other and connected through a longer wormhole tunnel. Moreover, in OLSR each node periodically sends routing control messages, which increases the load in dense networks. As these routing control messages are tunneled through the wormhole tunnel, the traffic increases dramatically, and congestion becomes inevitable through the path of that wormhole tunnel. This makes the legitimate nodes suspect and faultily identify some links as containing wormhole tunnels because of the increased delays.

Figure 6 presents the wormhole link detection rate for different HELLO$_{req}$ emission intervals and different wormhole attack durations when the number of nodes is 30. The graph elucidates the correlation between HELLO$_{req}$ emission intervals and wormhole attack durations. If the wormhole attack duration is shorter than the HELLO$_{req}$ emission interval, the wormhole link detection rate becomes poor (i.e., less than 0.5). This is due to the fact that there are some nodes that do not perform the HELLO$_{req}$-HELLO$_{rep}$ exchange procedure. Our approach shows a good detection rate after two HELLO$_{req}$ emission intervals. This result demonstrates the impact of the HELLO$_{req}$ emission interval on detection time. If the HELLO$_{req}$ emission interval is long enough, it takes more time to detect any wormhole tunnel. Therefore, an application that needs a high security level has to use small HELLO$_{req}$ emission intervals.

CONCLUSION

Wormhole attacks are severe attacks that can easily be launched even in networks with confidentiality and authenticity. Malicious nodes usually target the routing control messages related to topology or routing information. In this article we have presented an effective method for detecting and preventing wormhole attacks in OLSR. To detect wormhole tunnels, we use a simple four-way handshaking message exchange. The proposed solution is easy to deploy; it does not require any time synchronization or location information; nor does it require any complex computation or special hardware. The performance of this approach shows a high detection rate under various scenarios.

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BRAHIM BENSAOU [SM] (brahim@cse.ust.hk) received an engineering degree in computer science (with distinction) from USTHB in 1982 and a D.E.A. degree from the University of Paris XI in computer science in 1988. He earned his doctorate degree in computer science from the University of Paris VI in 1993. From 1990 to 1994 he was a research assistant at France Telecom Research Laboratories near Paris, where he was involved in the early designs and studies of ATM technology. In mid-1995 he joined the Hong Kong University of Science and Technology (HKUST) as a research associate, where he spent nearly two years working on various problems in congestion and traffic control. In 1997 he joined the Centre for Wireless Communications, a national R&D center in Singapore (now known as the Institute of Infocomm Research, I2R A-Star) as a member of technical staff, where he worked as a system architect on the design of QoS enabled MAC protocols and scheduling algorithms in a wireless prototype. ATM network prototype. In 1998 he was promoted to senior member of technical staff, and was instrumental in forming a small R&D group in the area of wireless networking at the CWC. He led the group for a year and a half, and then moved to academia at HKUST in fall 2000, where he is now a faculty member in the Department of Computer Science and Engineering. His general areas of research are in QoS enabled wireless networks, including ad hoc networks, sensor networks, and wireless LANs, on which he has published more than 80 research papers in prominent conferences and journals, received numerous research grants, graduated nearly 20 postgraduate students, four of which are Ph.D.s, and invented three U.S. patents, one of which is licensed. He is an Associate Editor of IEEE Communications Letters and a member of the ACM.

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