A Critical Analysis and Improvement of AACS Drive-Host Authentication

Jiayuan Sui and Douglas R. Stinson
David R. Cheriton School of Computer Science
University of Waterloo
Waterloo, ON, N2L 3G1, Canada
jsui@cs.uwaterloo.ca dstinson@uwaterloo.ca

Abstract

This paper presents a critical analysis of the AACS drive-host authentication scheme. A few weaknesses are identified which could lead to various attacks on the scheme. In particular, we observe that the scheme is susceptible to unknown key-share and man-in-the-middle attacks. Modifications of the scheme are suggested in order to provide better security. A proof of security of the modified scheme is also presented. The modified scheme achieves better efficiency than the original scheme.

1 Introduction

Advanced Access Content System (AACS) is a content distribution system for recordable and pre-recorded media. It has been developed by eight companies: Disney, IBM, Intel, Matsushita (Panasonic), Microsoft, Sony, Toshiba, and Warner Brothers. Most notably, AACS is used to protect the next generation of high definition DVD optical discs such as Blu-Ray and HD-DVD discs.

To design a media protection scheme that is able to run on open platforms like PCs, designers have to make sure that the scheme is not susceptible to the "Virtual Device Attack". A virtual device mimics a physical hardware device in all aspects so that the CPU is tricked into believing that a device exists when actually it does not. To deploy a virtual device attack on a media system such as the DVD playback system, the attacker can build software that implements a virtual DVD drive. The content of the optical disk is moved onto the computer hard drive as a disk image. The attacker can then play back this "DVD disk" through the virtual DVD drive on a legitimate DVD player software.

The attacker can certainly duplicate the image into multiple copies and disseminate them illegally, even though he never learns the content of the DVD in the clear. In order to defend against this attack, the drive has to have the ability to prove to the host (the playback software or the operating system, etc.) that it is a legitimate drive. This can be done through a cryptographic authentication protocol.

AACS drive-host authentication scheme achieves mutual authentication, which means that not only the drive proves to the host its legitimate identity but also the host has to prove its identity to the drive. After the drive and the host complete a successful session, a shared secret key is established between them. Therefore, AACS drive-host mutual authentication protocol is combined with a key agreement protocol. The shared secret key is then used for message authentication purposes.

In this paper, we present a rigorous analysis of the AACS drive-host authentication scheme. Specifically, we identify a few weaknesses present in the scheme which could lead to various attacks. Modifications of the scheme are suggested in order to provide better security. We also give a proof of security of our modified scheme.

1.1 Mutual Authentication Protocol and Key Agreement Protocol

In a mutual authentication protocol, the two participating entities need to prove their identities to each other. If an entity has successfully proven its identity to the other entity, the other entity is required to "accept". A session of a mutual authentication protocol is a successfully completed session if both participants have accepted by the end of the session. Mutual authentication protocols can be devised by using either symmetric or asymmetric key cryptographic primitives. This book chapter [8, Chapter 9] provides some good studies on mutual authentication protocols.

After two entities have authenticated themselves to each other, most likely they will want to communicate with each other. It therefore makes sense to combine a key agreement protocol with a mutual authentication protocol, because a shared secret key provides confidentiality and/or data integrity to both communicating entities. In a key agreement protocol, both entities contribute information which is used to derive a shared secret key. A key agreement protocol will most often be asymmetric.

A key agreement protocol is said to provide *implicit key authentication* to both entity A and entity B if A is assured that no one other than B can possibly learn the value of a particular secret key. Note that this property does not necessarily mean that A is assured of B actually possessing the key nor is A assured that B can actually compute the key. A key agreement protocol with implicit key authentication is called an *authenticated key agreement* (AK) protocol.

A key agreement protocol is said to provide *implicit key confirmation* if A is assured that B can compute the secret key while no others can. A protocol provides *explicit key confirmation* if A is assured that B has computed the secret key and no one other than B can compute the key. A key agreement protocol that provides key confirmation (either implicit or explicit) to both participating entities is called an *authenticated key agreement with key confirmation* (AKC) protocol. In general, explicit key confirmation is achieved by using the newly derived key to encrypt a known value and to send it to the other entity. In most cases, using a key agreement protocol with implicit key confirmation is sufficient. For more information on key agreement protocols, please refer to [8, Chapter 11].

1.2 Organization

In Section 2, we introduce the AACS drive-host authentication scheme. Our analysis of the AACS drive-host authentication scheme is presented in Section 3, where we identify several weaknesses in the scheme and provide corresponding improvements. In Section 4, we give a proof of security of the improved drive-host authentication scheme, followed by a conclusion in Section 5.

2 Description of AACS Drive-Host Authentication scheme

2.1 The basic procedure

When using AACS in a PC-based system where the drive and the host are separate entities, both the drive and the host are issued certificates from the AACS LA (AACS Licensing Administrator). This allows either entity to decide whether or not the other is trustworthy and in compliance with the AACS specifications. These certificates, called the *drive certificate* and *host certificate*, each contain fields stating the capabilities of the device, a unique identifier, the device's public key, and a signature from the AACS LA verifying the integrity of the certificate produced using an AACS LA private key. Both the drive and the host have the corresponding AACS LA public key. A full description of the certificate format can be found in the AACS Introduction and Common Cryptographic Elements specification [1, Chapter 4].

Authentication between the drive and host occurs each time new media is placed into the drive. This is necessary, due to the fact that the new disc may contain updated revocation lists. Each compliant disc contains a data structure called the Media Key Block (MKB), which holds the necessary information needed to derive the keys to decrypt the content. It also contains the latest Drive Revocation List (DRL) and Host Revocation List (HRL) which, respectively, contain a list of IDs of the revoked drives and a list of IDs of the revoked hosts. A drive may only communicate with a host that has not been revoked, and a host may only communicate with a drive that has not been revoked.

The following is a flow representation of the AACS drive-host authentication scheme (a detailed description can be found in [1, Section 4.3]). The numbers on each line correspond to the number given to that step in [1, Section 4.3].

The AGID sent in step 5 is the Authentication Grant Identifier, which is used to identify a specific session in the case where a drive can support connections from multiple hosts.

	Drive		Host
1.		$\xrightarrow{MKB}$	Compare version of stored DRL to DRL in MKB. If DRL in MKB is not newer, use stored DRL.
2.			If DRL in MKB is newer, verify DRL signature. Use DRL in MKB. Abort if signature is not valid.
3.	Compare version of stored HRL to HRL in MKB. If HRL in MKB is not newer, use stored HRL.		

4.	If HRL in MKB is newer, verify HRL signature. Use HRL in MKB. Abort if signature is not valid.		
5.		$\xrightarrow{AGID}$	
6.			Generate 160-bit nonce H_n.
7.		$\xleftarrow{H_n \| Hcert}$	
8.	Verify host certificate type and length. Abort on failure.		
9.	Verify signature on host certificate. Abort on failure.		
10.	Check HRL and abort if Host ID is found.		
11.			Request nonce D_n and drive certificate.
12.	Generate 160-bit nonce D_n.		
13.		$\xrightarrow{D_n \| Dcert}$	
14.			Verify drive certificate type and length. Abort on failure.
15.			Verify signature on drive certificate. Abort on failure.
16.			Check DRL and abort if Drive ID is found.
17.			Request a point on the elliptic curve D_v and its signature.
18.	Generate 160-bit random value D_k.		
19.	Calculate $D_v = D_k G$ where G is the base point of the elliptic curve.		

20.	Calculate D_{sig} as the signature of $H_n \| D_v$ using the drive's private key.		
21.		$\xrightarrow{D_v, D_{sig}}$	
22.			Verify D_{sig} and abort on failure.
23.			Generate 160-bit random number H_k.
24.			Calculate $H_v = H_k G$.
25.			Calculate H_{sig} as the signature of $D_n \| H_v$ using the host's private key.
26.		$\xleftarrow{H_v, H_{sig}}$	
27.	Verify H_{sig} and abort on failure.		
28.	Calculate Bus Key B_k as the 128 least significant bits of x-coord$(D_k H_v)$.		
29.			Calculate Bus Key B_k as the 128 least significant bits of x-coord$(H_k D_v)$.

After successfully completing the drive-host authentication algorithm, the drive and the host have established a shared *bus key* based on an elliptic curve Diffie-Hellman key agreement protocol [6]. It is interesting to note that while this key could be used to encrypt messages between the drive and host, it is not actually used for this purpose. Instead, the bus key is used solely for message authentication by including a MAC for any message traveling between the drive and the host. The current AACS specifications do not require either the drive or the host to be capable of encrypting and decrypting bus messages, however there is a flag in each certificate stating whether or not an entity is capable of performing bus encryption. The specifications simply state that a description of the bus encryption procedures will be given at a later date.

2.2 Requesting media-specific information

In the previous section, we saw how the drive and the host established a shared bus key. This bus key is used to ensure that communications between the drive and the host remain unaltered. In this section, we describe how the bus key is used when requesting certain values from the disc, such as the *volume ID* or the *binding nonce*. These are necessary when decrypting a disc, as they are used to derive the *title key*, which in turn is used to decrypt the content.

The protocol is simply a direct exchange of messages using MACs to ensure that the message is authentic. Figure 1 demonstrates the process in a protocol diagram. When the host makes a request for M, the drive reads it from the disc, computes a MAC using the bus key, and sends M in plaintext along with the MAC. Upon receiving the M, the host verifies the MAC and decides whether or not the message is valid.

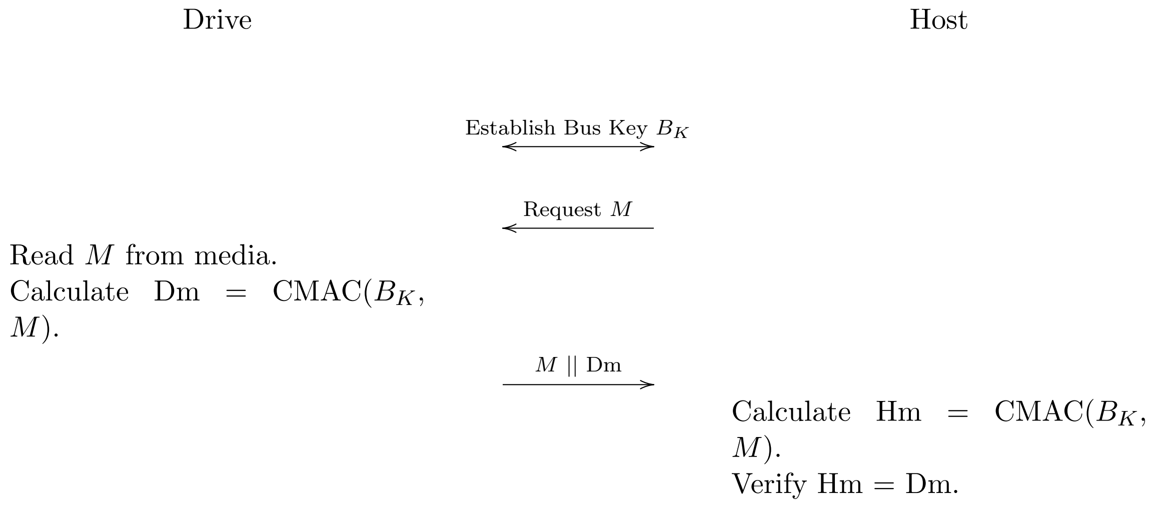


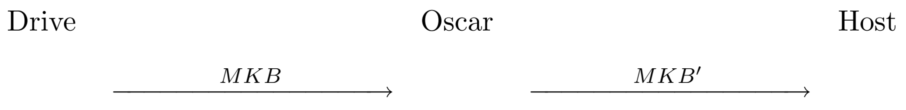
Figure 1: Protocol for Transferring Media-Specific Information.

3 Analysis of AACS Drive-Host Authentication scheme

In this section, we analyze the AACS drive-host authentication scheme. Several weaknesses are identified which could lead to various attacks, and corresponding improvements are provided to strengthen the original scheme.

3.1 Weakness 1: The DRL and HRL might not get updated.

This weakness is found in the first four steps of the drive-host authentication scheme. Suppose that the DRL on the MKB is newer than the DRL stored in the host. A malicious party, Oscar, can change the MKB version number to an older one, and send the modified MKB′ to the host. This modification might not be detected during the authentication procedure because, according to the specification, the host first checks the MKB version number, and if the version number is older than its DRL's, it skips over step 2, which involves verifying the signature on the DRL of MKB.



If the drive has already been revoked, it could maliciously alter the MKB version number in order not to let the host update its DRL, so that it can keep interacting with the host.

	Drive		Host
1.		$\xrightarrow{MKB}$	Verify MKB and DRL signatures. Abort if signatures are not valid.
2.			Compare version of stored DRL to DRL in MKB. If DRL in MKB is not newer, use stored DRL. Otherwise, use DRL in MKB.
3.	Verify MKB and HRL signatures. Abort if signatures are not valid.		
4.	Compare version of stored HRL to HRL in MKB. If HRL in MKB is not newer, use stored HRL. Otherwise, use HRL in MKB.		

Figure 2: Improved First Four Steps.

The altered MKB might eventually be detected when the host processes the MKB during content decryption. However, it is undesirable for a revoked drive to be able to talk to the host until then.

The fix to this weakness is simple: The host verifies the MKB and DRL signatures before checking the version numbers. The same modification can be made to the drive side. Figure 2 shows the modification.

3.2 Weakness 2: The scheme is susceptible to Unknown Key-Share attack

Suppose A and B are two honest participating entities trying to set up a shared secret key through a key agreement protocol, and O is an active malicious entity. An unknown key-share attack on a key agreement protocol is an attack through which O causes one of the two honest entities, say A, to believe that it shares a key with O, but it actually shares the key with the other honest entity B, and B believes that the key is shared with A. So, at the end of the protocol, O can act on behalf of B to interact with A. There are a number of papers studying unknown key-share attack and its application on a number of protocols, e.g. [2], [3], [5], [7], and [9].

We can simplify the original flow representation of the drive-host authentication scheme, as shown in Figure 3, by taking into consideration only the core steps involved in authentication and key agreement. A similar flow diagram is also provided in [1, Section 4.3].

1. Host initiates a session with Drive. It sends a random nonce H_n and its certificate H_{cert} to Drive. Drive verifies the signature of the Host certificate using the AACS LA public key. If the verification fails, Drive shall abort this authentication procedure.

$$\begin{tikzcd}
 & \text{Drive} & & \text{Host} \\
1. & {} & & {} \arrow[ll, "{H_n,\ H_{cert}}"'] \\
2. & {} \arrow[rr, "{D_n,\ D_{cert}}"] & & {} \\
3. & D_v{=}D_kG \arrow[rr, "{Sig_{drive}(H_n||D_v),\ D_v}"] & & {} \\
4. & {} & & H_v{=}H_kG \arrow[ll, "{Sig_{host}(D_n||H_v),\ H_v}"'] \\
5. & B_k{=}D_kH_v{=}D_kH_kG & & B_k{=}H_kD_v{=}H_kD_kG
\end{tikzcd}$$

Figure 3: Simplified AACS Drive-Host Authentication Protocol.

2. Drive replies to the Host with a random nonce D_n and its certificate D_{cert}. Host verifies the signature of the Drive certificate using the AACS LA public key. If the verification fails, Host shall abort this authentication procedure.

3. Drive generates a 160-bit random number D_k and uses it to calculate a point on the elliptic curve D_v (G is the base point of the elliptic curve). Drive then creates a signature of the concatenation of the nonce H_n and D_v. Drive sends the digital signature and D_v to Host. Host verifies the signature, and aborts the session on failure.

4. Host generates a 160-bit random number H_k and uses it to calculate a point on the elliptic curve H_v. Host then creates a signature of the concatenation of the nonce D_n and H_v. Host sends the digital signature and H_v to Drive. Drive verifies the signature, and aborts the session on failure.

On the last step, both Drive and Host calculate the shared secret bus key B_k.

An attacker, $\text{Drive}_{\text{Oscar}}$, which is also a legitimate drive, can use a parallel session to deploy an unknown key-share attack. Figure 4 shows the diagram of the attack.

The attack works in this way:

1. Host initiates a session with $\text{Drive}_{\text{Oscar}}$. It sends its random nonce H_n and certificate H_{cert} to $\text{Drive}_{\text{Oscar}}$.

2. $\text{Drive}_{\text{Oscar}}$ relays the traffic to Drive as if Host is initiating a session with Drive. Drive receives H_n and H_{cert} and verifies that H_{cert} is valid.

3. Drive sends back its random nonce D_n and certificate D_{cert} to Host, which of course get intercepted by $\text{Drive}_{\text{Oscar}}$.

4. $\text{Drive}_{\text{Oscar}}$ relays the random nonce D_n to Host, however, it does not relay the Drive's certificate. Instead, it sends its own certificate D_{O_cert} to Host. Host receives D_{O_cert} as well as D_n. It is tricked into believing that $\text{Drive}_{\text{Oscar}}$ has generated this random nonce. Host verifies $\text{Drive}_{\text{Oscar}}$'s certificate, and the verification should pass because $\text{Drive}_{\text{Oscar}}$ is a legitimate drive.

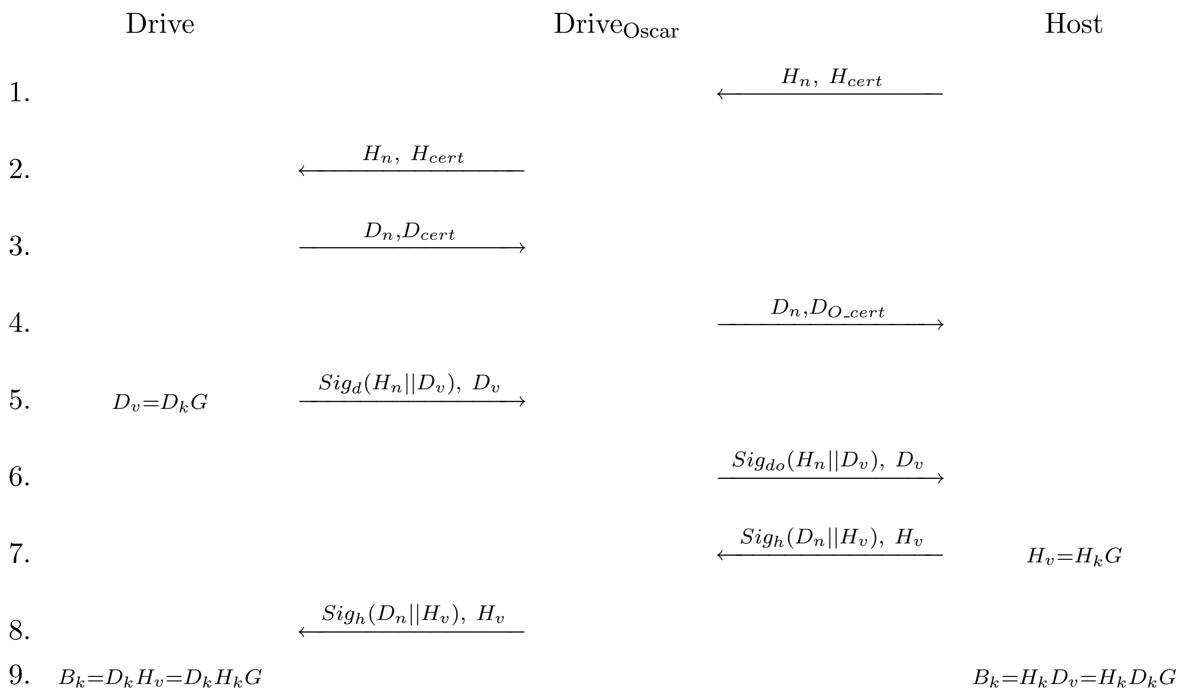


Figure 4: Unknow Key-Share Attack on AACS Drive-Host Authentication Protocol.

5. Following the AACS drive-host authentication protocol, Drive generates a random number D_k and calculates a point on the elliptic curve D_v. Drive then creates a signature of the concatenation of the nonce H_n and D_v. Drive sends the digital signature and D_v to Host.

6. Drive$_{\text{Oscar}}$ relays D_v to Host. However, it creates its own signature of the concatenation of the nonce H_n and D_v using its private key. It can do so because both H_n and D_v are available to it. It sends this signature instead of Drive's signature to Host. Host verifies the signature using Drive$_{\text{Oscar}}$'s public key obtained from D_{O_cert}. The verification should pass.

7. Host generates a random number H_k and calculates a point on the elliptic curve H_v. Drive then creates a signature of the concatenation of the nonce D_n and H_v. Drive sends the digital signature and H_v to Drive$_{\text{Oscar}}$.

8. Drive$_{\text{Oscar}}$ relays the traffic to Drive. Drive verifies the signature, and the verification should pass.

By the time the session is complete, Drive has accepted Host, and it can calculate the shared bus key B_k. On the other hand, Host does not accept Drive because it simply does not know the existence of Drive from this interaction. Instead, it has accepted Drive$_{\text{Oscar}}$. Host can also calculate the same shared bus key B_k.

Although Drive$_{\text{Oscar}}$ does not know the secret bus key B_k in the end, it has tricked Host into believing that it shares the bus key with Host. Host thinks that it is talking to Drive$_{\text{Oscar}}$ while actually it is interacting with Drive.

This attack could practically be exploited. For example, suppose that Drive$_{\text{A}}$ is revoked. Then it can employ this attack to ask Drive$_{\text{B}}$, which is not revoked, to impersonate it. Since the host only sees Drive$_{\mathrm{B}}$'s certificate, the authentication procedure should complete successfully. In this way, Drive$_{\mathrm{A}}$ can still interact with the host after the authentication procedure. It has effective bypassed the authentication procedure.

Such an attack is enabled due to the fact that in the last two flows Drive$_{\mathrm{Oscar}}$ can simply copy the traffic. This problem can be fixed by including the entity IDs in the signature. (See Section 3.4).

3.3 Weakness 3: The scheme is susceptible to Man-In-The-Middle attack

The adversarial goal in an attack to a mutual authentication protocol is to cause an honest participant to "accept" after a flow in which the adversary is active. To consider a mutual authentication protocol secure, it has to satisfy the following conditions:

1. Suppose A and B are the two participants in a session of the protocol and they are both honest. Suppose also that the adversary is passive. Then A and B will both "accept".

2. If the adversary is active during a given flow of the protocol, then no honest participant will "accept" after that flow.

Figure 5 shows an attack which might not be as powerful and practical as the previous one. Nonetheless, it shows a weakness in this protocol.

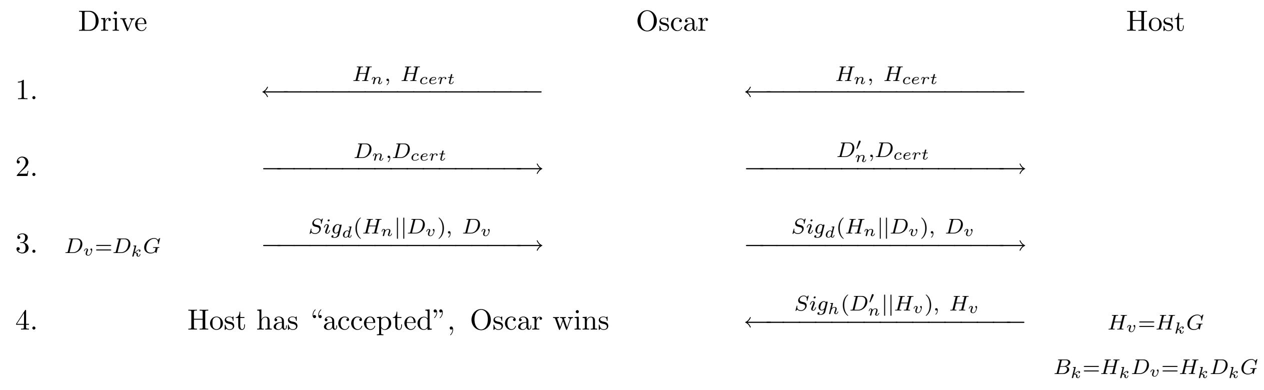

Drive
Oscar
Host
1.
$H_n,\ H_{cert}$
$H_n,\ H_{cert}$
2.
D_n, D_{cert}
D'_n, D_{cert}
3.
$D_v = D_k G$
$Sig_d(H_n || D_v),\ D_v$
$Sig_d(H_n || D_v),\ D_v$
4.
Host has "accepted", Oscar wins
$Sig_h(D'_n || H_v),\ H_v$
$H_v = H_k G$
$B_k = H_k D_v = H_k D_k G$

Figure 5: A Trivial Man-In-The-Middle Attack

In this case, Oscar could be a polynomial time adversary with the ability to listen and to modify the traffic. Notice that in step 2 when Oscar relays the traffic from Drive to Host, it modifies the random nonce D_n generated by Drive into a different one D'_n. This does not make Host terminate the session. In step 3, after Host has successfully verified Drive's signature, it "accepts". This violates condition 2 mentioned above, hence the protocol should not be considered secure.

A moment of reflection regarding this attack reveals that we do not really need the two nonces "H_n" and "D_n".

3.4 Improved Scheme

Since the scheme makes use of certificates, we can improve it using a simplified *Station-to-Station* protocol (STS). STS protocol is a key agreement scheme based on Diffie-Hellman scheme that provides mutual authentication. For more information on STS protocols, please refer to [4], [8, Chapter 11].

$$\begin{tikzcd}
 & \text{Drive} & & & \text{Host} \\
1. & & {} & {} \arrow[l, "{H_v,\ H_{cert}}"'] & H_v{=}H_kG \\
2. & D_v{=}D_kG & {} \arrow[r, "{Sig_{drive}(ID_{host}||D_v||H_v),\ D_v,\ D_{cert}}"] & {} & \\
3. & & {} & {} \arrow[l, "{Sig_{host}(ID_{drive}||H_v||D_v)}"'] & \\
4. & B_k{=}D_kH_v{=}D_kH_kG & & & B_k{=}H_kD_v{=}H_kD_kG
\end{tikzcd}$$

Figure 6: Improved Scheme Based on Station-to-Station Protocol

Figure 6 shows the modified drive-host authentication scheme based on STS. This modification solves both problems stated in weakness 2 and 3 (security proof is given in the next section). In addition, it improves the efficiency of the original protocol, because the number of interactions between Drive and Host is reduced.

1. Host initiates a session with Drive. It generates a 160-bit random number H_k and uses it to calculate a point on the elliptic curve H_v. It sends the H_v and its certificate H_{cert} to Drive. Drive verifies the signature of the Host certificate using the AACS LA public key. If the verification fails, Drive shall abort this session.

2. Drive generates a 160-bit random number D_k and uses it to calculate a point on the elliptic curve D_v. Drive then creates a signature of the concatenation of the Host ID, D_v, and H_v. Drive sends the digital signature, D_v, and its certificate D_{cert} to Host. Host verifies the signature created by Drive: $ver_{drive}(ID_{host}||D_v||H_v, \text{Drive's signature}) = \{\text{true, false}\}$, and it also verifies the signature of the Drive certificate. If any of the two verifications fail, Host shall abort the session.

3. Host creates a signature of the concatenation of the Drive ID, H_v, and D_v and sends it to Drive. Drive verifies the signature: $ver_{host}(ID_{drive}||H_v||D_v, \text{Host's signature}) = \{\text{true, false}\}$, and aborts the session on failure.

At the end of the protocol, both Drive and Host are able to establish the shared secret bus key B_k. Points H_v and D_v in this protocol also play a role as random challenges.

The following flow representation shows the entire modified drive-host authentication protocol.

$$\begin{tikzcd}
 & \text{Drive} & & & \text{Host} \\
1. & & {} \arrow[r, "MKB"] & {} & \text{Verify MKB and DRL signatures. Abort if signatures are not valid.}
\end{tikzcd}$$

2.			Compare version of stored DRL to DRL in MKB. If DRL in MKB is not newer, use stored DRL. Otherwise, use DRL in MKB.
3.	Verify MKB and HRL signatures. Abort if signatures are not valid.		
4.	Compare version of stored HRL to HRL in MKB. If HRL in MKB is not newer, use stored HRL. Otherwise, use HRL in MKB.		
5.		$\xrightarrow{AGID}$	
6.			Generate 160-bit random number H_k.
7.			Calculate $H_v = H_k G$ where G is the base point of the elliptic curve.
8.		$\xleftarrow{H_v \| Hcert}$	
9.	Verify host certificate type and length. Abort on failure.		
10.	Verify signature on host certificate. Abort on failure.		
11.	Check HRL and abort if Host ID is found.		
12.			Request a point on the elliptic curve D_v, signature, and drive certificate.
13.	Generate 160-bit random value D_k.		
14.	Calculate $D_v = D_k G$ where G is the base point of the elliptic curve.		

15.	Calculate D_{sig} as the signature of $ID_{host}\|D_v\|H_v$ using the drive's private key.		
16.		$\xrightarrow{D_{sig}\|D_v\|Dcert}$	
17.			Verify drive certificate type and length. Abort on failure.
18.			Verify signate on drive certificate. Abort on failure.
19.			Check DRL and abort if Drive ID is found.
20.			Verify D_{sig} and abort on failure.
21.			Calculate H_{sig} as the signature of $ID_{drive}\|H_v\|D_v$ using the host's private key.
22.		$\xleftarrow{H_{sig}}$	
23.	Verify H_{sig} and abort on failure.		
24.	Calculate Bus Key B_k as the 128 least significant bits of x-coord$(D_k H_v)$.		
25.			Calculate Bus Key B_k as the 128 least significant bits of x-coord$(H_k D_v)$.

The new protocol solves all the aforementioned problems. Since the random challenges H_n and D_n are omitted, it enables the drive and the host to perform fewer interactions, and therefore it is more efficient.

4 Security of the Modified Drive-Host Authentication Scheme

The modified scheme protects against unknown key-shared attack mentioned earlier.

In Figure 7, a question mark following a signature indicates that the adversary is unable to compute this signature. At step 3, the signature which Host sends to Drive$_{\text{Oscar}}$ contains Drive$_{\text{Oscar}}$'s ID not Drive's ID because Host believes that it is talking to Drive$_{\text{Oscar}}$. Drive$_{\text{Oscar}}$ cannot compute

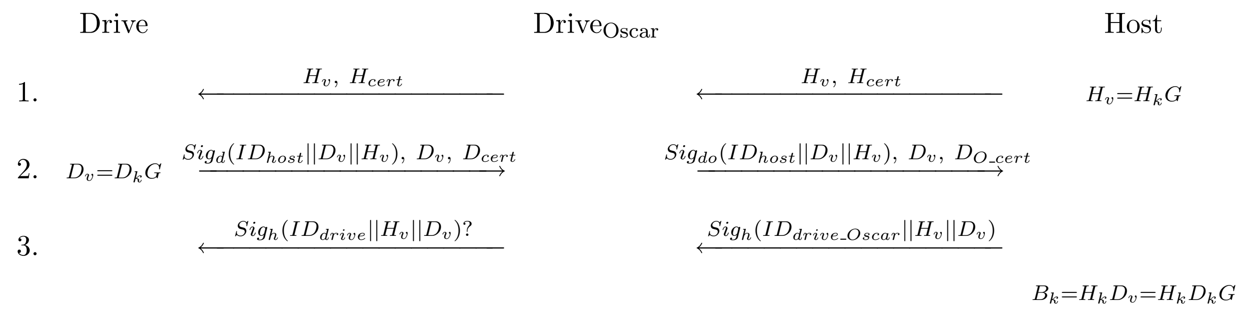

Drive
$\text{Drive}_{\text{Oscar}}$
Host
1.
$H_v,\ H_{cert}$
$H_v,\ H_{cert}$
$H_v{=}H_kG$
2.
$D_v{=}D_kG$
$Sig_d(ID_{host}||D_v||H_v),\ D_v,\ D_{cert}$
$Sig_{do}(ID_{host}||D_v||H_v),\ D_v,\ D_{O\_cert}$
3.
$Sig_h(ID_{drive}||H_v||D_v)?$
$Sig_h(ID_{drive\_Oscar}||H_v||D_v)$
$B_k{=}H_kD_v{=}H_kD_kG$

Figure 7: Prevention Against Unknow Key-Share Attack

Host's signature on the string $ID_{drive}||H_v||D_v$ because he does not know Host's private signing key. As a result, unknown key-share attack is thwarted.

After step 2, Host "accepts" the authentication because it should successfully verify $\text{Drive}_{\text{Oscar}}$'s signature and certificate. This does not violate the second condition of considering a mutual authentication protocol secure mentioned in Section 3.3, because Host is authenticating with $\text{Drive}_{\text{Oscar}}$.

The modified scheme also protects against man-in-the-middle attack.

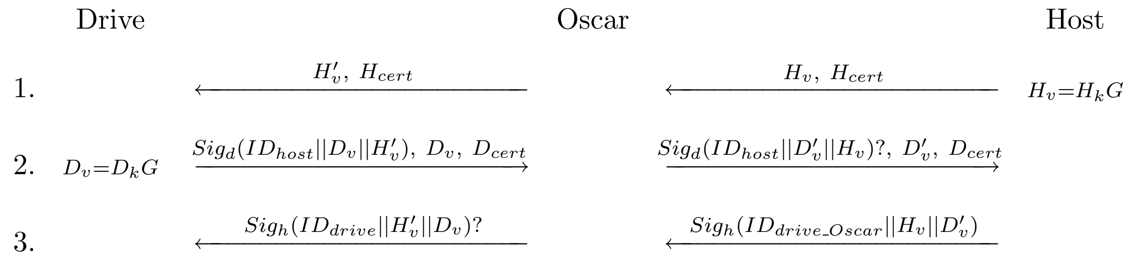

Drive
Oscar
Host
1.
$H'_v,\ H_{cert}$
$H_v,\ H_{cert}$
$H_v{=}H_kG$
2.
$D_v{=}D_kG$
$Sig_d(ID_{host}||D_v||H'_v),\ D_v,\ D_{cert}$
$Sig_d(ID_{host}||D'_v||H_v)?,\ D'_v,\ D_{cert}$
3.
$Sig_h(ID_{drive}||H'_v||D_v)?$
$Sig_h(ID_{drive\_Oscar}||H_v||D'_v)$

Figure 8: Prevention Against Man-In-The-Middle Attack

As shown in Figure 8, if Oscar modifies H_v, he then would not be able to produce Host's signature on $ID_{drive}||H'_v||D_v$ because he does not know Host's private signing key. Likewise, if Oscar modifies D_v, he then would not be able to produce Drive's signature on $ID_{host}||D'_v||H_v$ because he does not know Drive's private signing key.

Of course, we want to show that the modified scheme is secure against all possible attacks, not just two particular attacks. Hence, we need to show that the modified scheme is a secure mutual authentication scheme, and that it provides assurances regarding knowledge of the shared secret key.

4.1 The modified scheme provides secure mutual authentication

A secure mutual authentication has to satisfy the two conditions described in Section 3.3. Let us first show that our modified scheme satisfies the first condition.

Since no one is modifying the traffic, if the adversary is passive and the two participants are honest they should successfully authenticate themselves to each other and both compute the shared secret key as in the Diffie-Hellman key agreement scheme. Assuming the intractability of the *Decision Diffie-Hellman* problem, the inactive adversary cannot compute the share secret key.

To prove that our modified scheme satisfies the second condition, let us assume that the adversary is active. The adversary wants to fool at least one of the two participants to "accept" after a flow in which he is active. We show that the adversary will not scceed in this way, except with small probability.

Definition 1. A signature scheme is (ϵ, Q, T)-secure if the adversary cannot construct a valid signature for any new message with probability greater than ϵ, given that he has previously seen at most Q different valid signatures, and given that his computation time is limited to T.

Definition 2. A mutual authentication scheme is (ϵ, Q, T)-secure if the adversary cannot fool any honest participants into accepting with probability greater than ϵ, given that he has observed at most Q previous sessions between the honest participants, and given that the his computation time is at most T.

Time T is usually chosen to be very long so that by the time the adversary successfully computes the correct result the value of the result has decreased to an insignificant level. For simplicity of notation, we omit the time parameter. Q is a specified security parameter. Depending on the application, it could be assigned with various values. The probability ϵ is usually chosen to be so small that the chance of success is negligible.

Theorem 3. *Suppose that Sig is an (ϵ, Q)-secure signature scheme, and suppose that random challenges H_v and D_v are k bits in length. Then the scheme shown in Figure 6 is a $(Q/2^{k-1}+2\epsilon, Q)$-secure mutual authentication scheme.*

Proof. The adversary, Oscar, observes Q previous sessions of the protocol before making his attack. A successful attack by Oscar is to deceive at least one honest participant in a new session into accepting after he is active in one or more flows.

1. Oscar tries to deceive Host. In order to make Host accept, it has to receive a signature signed by Drive containing the Host ID and the random challenge H_v. There are only two ways for Oscar to acquire such a signature: either from a previously observed session or by computing it himself.

   To observe such a signature from a previous session, H_v has to be used in that session. The probability that Host has already used the challenge in a specific previous session is $1/2^k$. There are at most Q previous sessions under consideration, so the probability that H_v was used as a challenge in one of these previous sessions is at most $Q/2^k$. If this happens, Oscar can re-use Drive's signature and D'_v (which may or may not be the same as D_v) from that session to fool Host.

   To compute such a signature himself, Oscar has at most only a chance of ϵ, since Sig is (ϵ, Q)-secure.

   Therefore, Oscar's probability of deceiving Host is at most $Q/2^k + \epsilon$.

2. Oscar tries to deceive Drive. This is quite similar to the case we have discussed above. In order to fool Drive, Oscar has to have a legitimate signature signed by Host, i.e. $Sig_{host}(ID_{drive}||H_v||D_v)$. As in the previous case, the two ways for Oscar to acquire such a signature are either from a previously observed session or by computing it himself.

To observe such a signature from a previous session, D_v have to be used in that session (H_v could be re-used by Oscar). This happens with probability $1/2^k$. Oscar has observed at most Q sessions, so the probability for him to re-use Host's signature from a previous session is at most $Q/2^k$.

Again since Sig is (ϵ, Q)-secure, Oscar can compute such a signature with a probability of at most ϵ.

Therefore, Oscar's probability of deceiving Drive is at most $Q/2^k + \epsilon$.

Summing up, the probability for Oscar to deceive one of Host or Drive is at most $(Q/2^k + \epsilon) + (Q/2^k + \epsilon) = Q/2^{k-1} + 2\epsilon$. $\square$

4.2 The modified scheme provides implicit key confirmation

Now, let us see what we can infer about the modified scheme if Host or Drive "accepts". Firstly, suppose that Host "accepts". Because the modified scheme is a secure mutual authentication scheme, Host can be confident that it has really been communicating with Drive and that the adversary was inactive before the last flow. Assuming that Drive is honest and that it has executed the scheme according to the specifications, Host can be confident that Drive can compute the value of the secret bus key, and that no one other than Drive can compute the value of the bus key.

Let us consider in more detail why Host should believe that Drive can compute the bus key. The reason for this belief is that Host has received Drive's signature on the values H_v and D_v, so it is reasonable for Host to infer that Drive knows these two values. Now, since Drive is a honest participant and executed the scheme according to the specifications, Host can infer that Drive knows the values of D_k. Drive is able to compute the value of the bus key, provided that he knows the values of H_v and D_k. Of course, there is no guarantee to Host that Drive has actually computed the bus key at the moment when Host "accepts". We can be sure that no one else can compute the bus key because D_k is meant to be known to Drive only.

The analysis from the point of view of Drive is very similar. If Drive "accepts", then it is confident that it has really been communicating with Host, and that the bus key can be computed only by Host and no one else.

The modified scheme does not make immediate use of the new bus key, so we do not have explicit key confirmation. However, it does achieve implicit key confirmation. Moreover, it is always possible to augment any key agreement scheme with implicit key confirmation so that it achieves explicit key confirmation, if so desired. In essence, the modified scheme provides authenticated key agreement with key confirmation.

5 Conclusion

Through rigorous analysis of the AACS drive-host authentication scheme, we have observed a few weaknesses present therein. Specifically, the scheme is susceptible to unknown key-share attack and man-in-the-middle attack. As a goal to improve the scheme to resist all kinds of attacks, we have modified the original scheme based on a simplified Station-to-Station protocol to provide secure mutual authentication as well as authenticated key agreement with key confirmation. In addition, our modified scheme achieves better efficiency than the original scheme.

References

[1] AACS LA, "Advanced Access Content System (AACS) - Introduction and Common Cryptographic Elements, Revision 0.91", February 17, 2006, `http://www.aacsla.com/specifications/specs091/AACS_Spec_Common_0.91.pdf`

[2] J. Baek, K. Kim, "Remarks on the Unknown Key Share Attacks", IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, Vol. E83-A, No. 12, pp. 2766-2769, 2000.

[3] S. Blake-Wilson and A. Menezes, "Unknown Key-Share Attacks on the Station-to-Station (STS) Protocol", Proceedings of PKC 99, LNCS Vol. 1560, pp. 154-170, 1999.

[4] W. Diffie, P. C. van Oorschot, and M. J. Wiener, "Authentication and Authenticated Key Exchanges", Designs, Codes and Cryptography, Vol. 2, Issue 2, pp. 107-125, Kluwer Academic Publishers, 1992.

[5] B. S. Kaliski Jr., "An Unknown Key-Share Attack on the MQV Key Agreement Protocol", ACM Transactions on Information and System Security, Vol. 4, No. 3, pp. 275-288, 2001.

[6] National Institute of Standards and Technology, "Special Publication 800-56A, Recommendation for Pair-Wise Key Establish Schemes Using Discrete Logarithm Cryptography", March 2007.

[7] K. Shim, "Unknown Key-Share Attack on Authenticated Multiple-Key Agreement Protocol", Electronics Letters, Vol. 39, Issue 1, pp. 38-39, 2003.

[8] D. R. Stinson, "Cryptography Theory and Practice, Third Edition", Chapman & Hall/CRC, 2006.

[9] H. Zhou, L. Fan, and J. Li, "Remarks on Unknown Key-Share Attack on Authenticated Multiple-Key Agreement Protocol", Electronics Letters, Vol. 39, Issue 17, pp. 1248-1249, 2003.