Effective Caching for the Secure Content Distribution in Information-Centric Networking

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Abstract—The secure distribution of protected content requires consumer authentication and involves the conventional method of end-to-end encryption. However, in information-centric networking (ICN) the end-to-end encryption makes the content caching ineffective since encrypted content stored in a cache is useless for any consumer except those who know the encryption key. For effective caching of encrypted content in ICN, we propose a novel scheme, called the Secure Distribution of Protected Content (SDPC). SDPC ensures that only authenticated consumers can access the content. The SDPC is a lightweight authentication and key distribution protocol; it allows consumer nodes to verify the originality of the published article by using a symmetric key encryption. The security of the SDPC was proved with BAN logic and Scyther tool verification.

Index Terms— Information-Centric Networking, Content Distribution, In-network Caching, Authentication, Effective Caching

I. INTRODUCTION

INCE the earliest time of the Internet, its underlying Architecture has been based on packet-switching and hostto-host communication. The TCP/IP layered architecture employs the same view and provides an abstract host-to-host communication model to communication applications. However, in the recent past there has been a profound increase in Internet connectivity, and with the emergence of new Internet applications, the Internet semantics have changed from host centric to content centric. To satisfy the needs of emerging internet applications, the current TCP/IP Internet architecture has adopted several application layer solutions known as Overthe-Top (OTT) applications, such as Content Delivery Network (CDN), web caching, and peer-to-peer networking [1-3]. The additions of new OTT applications are leading us towards a very complex internet architecture, and are introducing challenges to achieving efficiency, security, privacy etc.at acceptable economical cost. In this perspective, Information-Centric Networking (ICN) has emerged as a promising architecture for the Future Internet.

ICN represents a paradigm shift from host-centric to contentcentric services and from a Source-driven to Receiver-driven approach. In the ICN paradigm the network is then in charge of doing the mapping between the requested content and where it can be found. To do so, network level naming is used for identifying content objects, independent of their location or container [4]. This means that the ICN architecture decouples content from the host at the network level and supports the temporary storage of content in an in-network cache [5-6]. The benefits of the ubiquitous caching in ICN are profound, but it also introduces a challenge to content security.

In an earlier work [7], the author presented a scheme for protected content using network coding as encryption. However, that scheme requires a private connection between the publisher and consumer to obtain the decoding matrix and some missing data blocks. In another study [8], the author presented a security framework for the distribution of encrypted copyright video streaming in ICN. However, each video was encrypted with a large number of symmetric encryptions keys, such that each video frame was encrypted with a unique symmetric encryption key. Only authorized users who possessed the set of all keys could decrypt the video content. The distribution of a large number of keys for each video content is an extra communication overhead.

A. Problem statement

The distribution of protected content requires the authentication of the consumer and involves a conventional type of end to end encryption. However, in information-centric networking (ICN) the end-to-end encryption for each authorized subscriber makes the content caching ineffective.

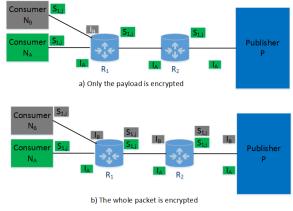


Figure 1 The ineffective caching in ICN with end-to-end encryption

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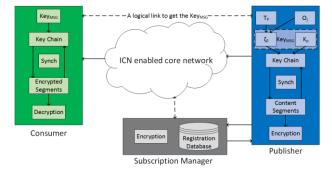
As shown in Figure 1, the consumers N_A and N_B subscribe to the protected content. Consumer N_A sent an interest packet I_A encapsulating authorization information for the content. In reply, based on the subscription information, the publisher Pauthenticates the consumer and checks the authorization of content object O_j for the consumer N_A . If N_A is a valid subscriber than publisher P encrypts the requested content segment $S_{1,j}$ and sends it to consumer N_A , encrypted with a consumer specific key. Based on the basic semantics of the information-centric networking (ICN), the intermediate cache routers R_1 and R_2 stores the encrypted content segment $S_{1,j}$, for future use.

In the next step, consumer N_B requests the same content. As shown in Figure 1-a, if the meta data of the encrypted stored packet is available to R_1 , then based on the basic semantics of ICN the intermediate cache router R_1 will reply with the cached content $S_{1,j}$ to consumer N_B . However, consumer N_B cannot decrypt the content segment $S_{1,j}$ as it was solely intended for consumer N_A .

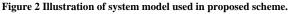
On the other hand, as shown in Figure 1-b, if the meta data of the encrypted stored packet is unavailable to R_1 , that is, the meta data is also encrypted, then the interest packet I_B will be forwarded to the publisher. If N_A is a valid subscriber then publisher *P*will encrypt the requested content segment $S_{1,j}$ and send it to consumer N_A , encrypted with a consumer specific key.

The solution is to encrypt each content segment with a key known to all subscribers; which raises three fundamental questions. How does one ensure that only an authenticated subscribed consumer can access the content? How can the consumer verify the originality of the published article; that is, do we still need self-certifying? Finally, and most importantly, how can encryption keys be distributed among all of the consumers for each content segment? We will answer all these questions in this work.

The remainder of this paper is organized as follows. In Section II, we present a brief system model overview. Section-III describes the proposed scheme with a detailed discussion. In Section-IV, we assess the strength of using BAN logic and Scyther verification. Finally, we provide concluding remarks in Section -V.



II. SYSTEM MODEL AND SKETCH OF PROPOSED SCHEME



The system model used throughout this work is shown in Figure 2. To enable the ICN core network to support the effective caching of encrypted content we introduce a new entity, designated subscription manager M. We assume that there is a secret number n_S^i associated with each valid subscriber consumer that is known to the subscription manager M, that is, the valid consumers are already registered with the subscription manager M. Note that being registered doesn't mean the consumer is entitled to access certain protected content. Moreover, subscription manager M can be a module installed on the publisher or it could be an independent entity in the network.

In this work we assume that subscription manager *M* is an independent entity associated with multiple publishers. This design reduces the message exchange complexity for the case when a consumer decides to subscribe to multiple protected contents published by different publishers.

When a registered consumer is interested in protected content they first need subscribe to the protected content, for instance, subscribing to a movie channel. In the first step, the consumer sends an interest request for the protected content along with the subscription request, and the publisher node routes the request towards subscription manager M. The subscription manager M authenticates consumer N_A and in response publisher *P* sends the encryption key generation information Key_{MSG} . Using Key_{MSG} as a seed for a simple hash function, consumer N_A and publisher P can generate a chain of keys. Publisher P uses these keys to encrypt the segments of the published content; likewise, after acquiring Key_{MSG} consumer N_A generates the same keys to decrypt the segments of the published content. Detailed descriptions of the key generation and secure subscription are discussed in subsequent sections.

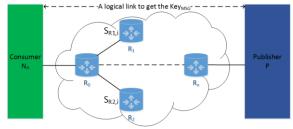


Figure 3An example of secure delivery of protected content

Let's consider the case where consumer N_A is already a registered consumer node. As shown in Figure 3, consumer N_A sends an interest packet $I_{A,i}$ encapsulating authorization information for the protected content object O_i . Let us say that protected content object O_i is composed of k number of segments $S = \{S_{1,i}, S_{2,i} \dots S_{k,i}\}$; further, the intermediate cache routers R_1 and R_2 have copies of the protected content segments, represented by $S_{R1,i} \subseteq S$ and $S_{R2,i} \subseteq S$. If N_A is a valid subscriber then publisher P sends the encryption key generation information Key_{MSG} to consumer N_A . After receiving the key generation information, the consumer can decrypt the content segments, which may be delivered directly from the intermediate cache router.

III. PROPOSED SCHEME

The SDPC protocol suite consists of two protocol suites, the Keying Protocol suite and the Subscription and Content Access Protocol suite. The Keying Protocol suite is comprised of a key generation protocol and a key agreement protocol for content protection. Likewise, the Content Access Protocol further comprises four protocols, one dealing with the consumer node subscription and the other three dealing with access to the protected contents published by the different types of publishers. The SDPC protocol suite is described in detail in subsequent sections.

A. Keying Protocol Suite

In the keying protocol suite, the key generation protocol generates a 'commitment key' using an irreversible function similar to the ones used in [9-10]. The 'commitment key' is further used to drive multiple keys.

The key generation mechanism for the content protection is shown in Figure 4 and consists of the following steps: 1) The publisher divides the large contents into equal sized segments. 2) For each protected content object O_i the publisher generates a unique commitment key generator by using an irreversible one way hash function $\zeta_0^j = H(T_P, O_j)$, where T_P is the time of publishing and O_i represents the content name and version. 3) The publisher now generate a "Chain of Key Generators" of length $L = \frac{sizeof(O_j)}{segment \ size}$ by using an irreversible one-way function: $\{H(\zeta_0^j) = \zeta_1^j, H(\zeta_1^j) = \zeta_2^j \dots H(\zeta_{l-1}^j) = \zeta_l^j\};$ i-e $H(\zeta_k^j)^i = \zeta_{k+i}^j$. 4) Each generator (ζ) in the chain is used by function g at a specific index location in the chain to derive a content segment encryption key. For instance, at index k the function $g(\zeta_k^j) = H(\zeta_k^j, K_p)$ generates the key K_k^j used for encrypting the kth segment of the content object O_i , where K_n is the public key of the publisher.

$$\begin{array}{c} \leftarrow \text{Key Generation} \\ \Rightarrow \text{Key Admission} \end{array} \zeta_{l}^{j} \xrightarrow{H(\zeta_{l-1}^{j})} \zeta_{l-1}^{j} & \longleftrightarrow \xrightarrow{H(\zeta_{1}^{j})} \zeta_{1}^{j} \xrightarrow{H(\zeta_{0}^{j})} \zeta_{0}^{j} \\ & \downarrow g(\zeta_{l}^{j}) & \downarrow g(\zeta_{l-1}^{j}) & \downarrow g(\zeta_{1}^{j}) & \downarrow g(\zeta_{0}^{j}) \\ \text{Segment} \\ \text{encryption key} & K_{l}^{j} & K_{l-1}^{j} & K_{1}^{j} & K_{0}^{j} \end{array}$$

Figure 4 Symmetric keys generation and admission with reference to segment number of protected content

The symmetric keys generated as a result of SDPC keying protocol have size of 256 bits (32 bytes); hence, in the subsequent section of authentication protocols any symmetric encryption supporting the 256-bit key can be used, e.g., RC5/6; Rijndael, Twofish, MARS, and Blowfish symmetric encryption algorithms support the 256-bit encryption key.

B. Subscription and Content Access Protocol suite

When a consumer wants to subscribe to the protected content, for instance a movie database, they gain initial access using a subscription protocol (SubP). After SubP the consumer can use the ticket to access multiple protected contents published by the publishers, or managed by a third party. In subsequent sections, the Subscription and Content Access Protocol suite are described in detail.

a) Initial Access and Subscription Protocol (SubP)

If a consumer node N_i wants to subscribe to the protected content, for instance subscribing for the movie channel, in the

first step, N_i generates an encryption key $K_{TS}^i = H(K_p^j \oplus n_S^i)$, where K_p^j is the public key of publisher and n_S^i is a secret number shared with the subscription manager M. The consumer sends an interest request for the protected content along with the subscription request, encrypting the secret number n_S^i with K_{TS}^i . The publisher node routes the request towards M, and the protocol continues as follows:

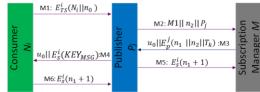


Figure 5 Message exchange for initial access and subscription protocol

- M1. As shown in Figure 5, N_i injects a subscription interest packet I_i . The ICN core network forwards it to the publisher P_j . The interest packet encloses the n_0^i which is encrypted with the generated encryption key K_{TS}^i .
- M2. Upon receiving the request from N_i , the P_j forwards the request in conjunction with its identity and challenge n_2 to the subscription manager M. Note that P_j cannot decrypt the part of the interest packet, which is encrypted with key K_{TS}^i and holds the secret registration number n_s^i .
- M3. *M* retrieves the profile from the database, and if N_i is a legitimate consumer, *M* generates the keys $K_{TS}^i = H(K_p^j \oplus n_s^i)$, $K_s^i = H(T_M \oplus n_s^i)$, and sends $u_0 = E_{TS}^i(n_s^i + 1 ||n_1||T_k||K_s^i)$ to P_j in M3, T_M is the time of issuing the session key K_s^i . M3 also includes ticket $T_k = E_P^j(N_i||K_s^i|| profile)$, n_1 (a challenge for N_i), and n_2 (challenge response for the P_j), all encrypted with K_p^j . The publisher P_j verifies the challenge n_2 , stores n_1 and retrieves the profile and K_s^i from the ticket. Note that the ticket is encrypted with the public key of the publisher. The consumer node N_i cannot decrypt it, but can use it to subscribe to other contents published by the publisher P_j , without contacting subscription manager M.
- M4. P_j forwards the u_0 to N_i along with the $KEY_{MSG} = (\zeta_0^j, K_p)$, which is required to decrypt the segments of the published content. After a challenge $(n_0^i + 1)$ verification, N_i accepts T_k and generates the key chain to decrypt the protected published content. The key chain is generated using the public key of P_j , hence, the content is also self-certifying.
- M5. P_j sends the challenge response $(n_1 + 1)$ to M for the confirmation of a successful protocol run.
- M6. After challenge $(n_1 + 1)$ confirmation, P_j may optionally register the N_i in its own database. If P_j does not receive a challenge response within a certain period of time, then P_j marks T_k as a stolen ticket.

In the SubP, a secure exchange of n_0 ensures the message authentication between the consumer and the publisher, n_2 between the publisher and subscription manger, and n_1 between the subscription manger and the publisher, while message

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authentication between the consumer and publisher is established by session key encryption and n_1 .

b) Content Access Protocols

(1) Access Protocol after Subscription (APSub)

Further, if consumer N_i wishes to access some other protected contents published by the publisher P_j , then N_i sends an interest request for the protected content along with the ticket T_k and the protocol continues as follows:

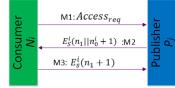


Figure 6 Message exchange for access protocol after subscription

- M1. As shown in Figure 6, N_i injects a subscription interest packet, enclosing $Access_{req} = E_S^i(N_i ||n_0)||T_k$. The ICN core network forwards it to the publisher P_j . The publisher P_j decrypts the ticket, retrieves K_S^i , verifies sender identity N_i . If the value N_i does not match, the P_j will ignore the request and otherwise proceed as follows.
- M2. P_j sends a challenge response along with the new challenge encrypted with session key K_s^i . P_j also send the Key_{MSG} , which is required to decrypt the segments of the published content.
- M3. N_i sends the challenge response n_1 . If P_j does not receive the challenge response within a certain period of time, then P_j marks T_k as a stolen ticket.

In the above APSub, the secure exchange of n_0^i ensures the message authentication between the consumer and the publisher.

(2) Access Protocol after Subscription involving a Third party (APSub3)

Assume a consumer N_i subscribed with P_i , which means it shares a session key K_s^i with P_i and holds a T_k encrypted with public key of P_i . Now if N_i wishes to access the protected contents published by a third-party content publisher P_j , APSub3 continues as follows:

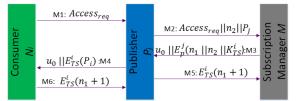


Figure 7 Message exchange for access protocol after subscription involving a third party

- M1. As depicted in (3) at Figure 3-b, N_i injects a subscription interest packet enclosing $Access_{req} = E_s^i(N_i || n_0) || T_k$ and the packet is forwarded to the publisher P_i .
- M2. Upon receiving the request from N_i , P_j forwards the request in conjunction with its identity and the challenge n_2 to M. Note that P_j cannot decrypt $Access_{req}$ in the interest packet, which is encrypted with a shared session

- key K_s^i between N_i and P_i , which ensures the third-party content distributor cannot misuse the consumer secure information, such as profile and secret share number etc.
- M3. *M* retrieves the profile from T_k , and if N_i is a legitimate consumer, *M* generates the key $K_{TS}^i = H(K_s^i \bigoplus n_0)$, and sends $u_0 = E_s^i(n_0 + 1 ||n_1|| Key_{MSG})$ to P_j . The message M3 also includes the key K_{TS}^i , n_1 a challenge for N_i , and n_2 the challenge response for P_j , which are encrypted with public key pf P_j . After that, the publisher P_j verifies the challenge response n_2 and stores n_1 . Note that the ticket is encrypted with the public key of P_i . Therefore, N_i and third-party publisher P_j cannot decrypt it. Also, Key_{MSG} is inaccessible to P_i , which ensures that the third-party content distributor cannot misuse the protected content.
- M4. P_j forwards $u_0 || E_{TS}^i(P_j)$ to N_i . After the verification of the challenge $(n_0 + 1)$, N_i generates $K_{TS}^i = H(K_S^i \oplus n_0)$ and sends the challenge response $(n_1 + 1)$ to P_j . Now N_i can generate a key chain to decrypt the protected published content. Since the key chain is generated using the public key of P_i , the content is also self-certifying.
- M5. P_j sends the challenge response $(n_1 + 1)$ to M for the confirmation of a successful protocol run.
- M6. After the challenge confirmation, P_j closes the protocol run. If P_j does not receive any challenge response within a certain period of time, P_j marks T_k as a stolen ticket.

In SubP3, secure exchanges of n_0 , n_1 , and n_2 ensure the message authentication between the consumer and the subscription manger, between the subscription manger and the third-party publisher, and between the third-party publisher and subscription manger, respectively. On the other hand, the message authentication between the consumer and the third-party publisher is established by a temporary session key K_{TS}^i and n_1 .

C. MPEG Video Distribution: An application of the proposed scheme

This section briefly explains how our proposed scheme can be used for the effective distribution of protected MPEG video in ICN. In MPEG the video is defined as a stream of a group of pictures (GOPs). As shown in Figure 8, each GOP consists of one I frame (Intra-coded picture) and multiple P (Predicted picture) and B (Bidirectional predicted picture) frames. To recover the video in its real quality most of the information is stored in the I-Frame. If a publisher P_i publishes a protected MPEG video, by encrypting the I-Frame the video remains protected. The partial encryption of each GOP is the same as the method employed in [7] but with SDPC the subscriber can generate a large number of keys with the exchange of just a single commitment key.

Using our proposed scheme, the publisher P_i generates a chain of keys for the protected content object O_j and encrypts the I-Frame in each GOP using a corresponding key from the key chain; for instance the I-frame of GOP1 is encrypted with K_1^j . When a consumer N_i injects the first interest packet,

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whether enclosing a subscription or access request, the publisher P_j sends the Key_{MSG} to consumer N_i . Meanwhile, the intermediate custodian nodes transfer the data to consumer N_i . The consumer N_i then generates the chain of keys and decrypts all of the I-Frame segments using the corresponding keys.

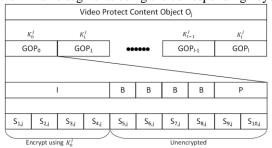


Figure 8 The structure of video content and usage of SDPC keying protocol.

IV. SECURITY ANALYSIS

This section presents an inclusive security analysis of the SDPC protocol using BAN logic [11], and also presents the Scyther [12] implementation result of the SDPC.

A. Formal security analysis using BAN logic

BAN logic [11] is widely used for the formal analysis of security protocols. To verify the security of the SDPC protocol suite it is sufficient to demonstrate the security of the SubP protocol; the rest of the protocols are extensions of the SubP, which use the ticket and session key established in the SubP protocol run. The three basic objects of BAN logic are principals, formula/statements, and encryption keys. The principals, the protocol participants, are represented by symbols P and Q. The formula/statements are symbolized by X and Y and represents the content of the message exchanged. The encryption keys are symbolized by K. The logical notations of BAN-logic used for our analysis is given below:

- $P \models X: P$ believes X, or P would be enabled to believe X; in conclusion, P can take X as true.
- *P* < *X*: *P* sees/receives *X*. *P* initially has or received a message *X* and *P* can see the contents of the message and is capable of repeating *X*.
- *P*|~*X*: *P*once said *X*. *P* has sent a message including the statement *X*. However, the freshness of message is unknown.
- $P \Longrightarrow X: P$ controls X and should be trusted for formula/statement X.
- #(X): X is fresh; it says, X never sent by any principal before.
- $P \stackrel{K}{\longleftrightarrow} Q:P$ and Q shares a key K to communicate in a secure way and K is only known to P, Q and a trusted principal.
- $(X)_K$: The statement X is encrypted by key K.
- {*X*}_{*Y*}: It stand for *X* combined with *Y*. *Y* is anticipated to be secret and its implicit or explicit presence proves the identity of a principal who completes the {*X*}_{*Y*}.

Some primary BAN-logic postulates used in the analysis of

the SDPC are given below:

- Message meaning rules: $\frac{P \models P \longleftrightarrow Q, P \lt (X)_K}{P \models Q \mid \sim X}, \frac{P \models P \longleftrightarrow Q, P \lt \{X\}_Y}{P \models Q \mid \sim X}$
- Nonce verification rule: $\frac{P \models \#(X), P \models Q \mid \sim X}{P \models Q \models X}$
- Jurisdiction rule: $\frac{P \models Q \Longrightarrow X, P \models Q \models X}{P \models V}$
- Freshness rule: $\frac{P \models \#(X)}{P \models (X,Y)}$
- Believe rule: $\frac{P \models Q \models (X,Y)}{P \models X, P \models Y}$

a)

• Session key rule: $\frac{P \models Q \#(X), P \models Q \models X}{P \models P \longleftrightarrow Q}$

Ban Logic Analysis of SubP:

The *SubP* protocol should achieve the following goals which states that both the consumer and the publisher trust the encryption key K_S^i for the secure exchange of KEY_{MSG} :

1. $N_i \models (N_i \stackrel{K_s^i}{\longleftrightarrow} P_j)$ 2. $N_i \models P_j \models (N_i \stackrel{K_s^i}{\longleftrightarrow} P_j)$ 3. $P_i \models (N_i \stackrel{K_s^i}{\longleftrightarrow} P_i)$

4.
$$P_j \models N_i \models (N_i(N_i \stackrel{K_S^i}{\leftrightarrow} P_j))$$

Protocol Idealization:

$$\begin{split} & \text{M1. } N_{i} \stackrel{Via \ P_{j}}{\longleftrightarrow} M: \left\{ n_{0}, \left(N_{i} \stackrel{n_{S}^{i}}{\leftrightarrow} M \right) \right\}_{H(X_{S})} \\ & \text{M2. } P_{j} \rightarrow M: \left\{ n_{2}, \ IDP_{j} \right\} \\ & \text{M3. } M \rightarrow P_{j}: \left\{ \left(n_{1}, n_{2}, \left(N_{i} \left(\stackrel{K_{S}^{i}}{\leftrightarrow} \right) P_{j}, \# \left(N_{i} \left(\stackrel{K_{S}^{i}}{\leftrightarrow} \right) P_{j} \right) \right)_{K_{p}^{j}} \right)_{K_{p}^{j}} \right)_{K_{p}^{j}} , \left\{ n_{0}, n_{1}, \left(N_{i} \left(\stackrel{K_{S}^{i}}{\leftrightarrow} \right) P_{j} \right)_{K_{p}^{j}} , N_{i} \left(\stackrel{K_{S}^{i}}{\leftrightarrow} \right) P_{j} \right)_{K_{p}^{j}} , N_{i} \left(\stackrel{K_{S}^{i}}{\leftrightarrow} \right) P_{j} , \# \left(N_{i} \left(\stackrel{K_{S}^{i}}{\leftrightarrow} \right) P_{j} \right)_{K_{p}^{j}} , N_{i} \stackrel{K_{S}^{i}}{\leftrightarrow} N_{i} \right\}_{H(X_{S})} \end{split} \\ & \text{M4. } P_{j} \stackrel{Via \ M}{\longleftrightarrow} N_{i}: \left\{ n_{0}, n_{1}, \left(N_{i} \stackrel{K_{S}^{i}}{\leftrightarrow} P_{j} \right), \# \left(N_{i} \stackrel{K_{S}^{i}}{\leftrightarrow} P_{j} \right) \right\}_{H(X_{S})} \\ & \text{M5. } P_{j} \rightarrow N_{i}: \left(KEY_{MSG} \right)_{K_{S}^{i}} \\ & \text{M6. } N_{i} \rightarrow P_{j}: \left(n_{1} \right)_{K_{S}^{i}} \\ & \text{Initial State Assumptions:} \\ & \text{A1. } M \models \# \left(n_{0} \right) \\ & \text{A2. } M \models \# \left(n_{1} \right) \\ & \text{A4. } N_{i} \models \# \left(n_{1} \right) \\ & \text{A5. } N_{i} \models \left(N_{i} \stackrel{K_{TS}=H(X_{S})}{\longleftrightarrow} M \right) \end{aligned}$$

A6.
$$M \models \left(N_i \xleftarrow{K_{TS} = H(X_S)}{M}\right)$$

A7. $P_j \models \left(P_j \xleftarrow{K_P^j}{M}\right)$
A8. $M \models \left(P_j \xleftarrow{K_P^j}{M}\right)$

A9.
$$M \models N_i \models \left(N_i \stackrel{K_{TS}=H(X_S)}{\longleftrightarrow} M\right)$$

A10. $N_i \models M \models \left(N_i \stackrel{K_{TS}=H(X_S)}{\longleftrightarrow} M\right)$
A11. $M \models P_j \models \left(P_j \stackrel{K_p^j}{\leftrightarrow} M\right)$
A12. $P_j \models M \models \left(P_j \stackrel{K_p^j}{\leftrightarrow} M\right)$

Let us analyze the protocol to show that N_i and P_j share a session key:

From M1, we have $M \leq \left\{ n_0, \left(N_i \stackrel{n_S^i}{\leftrightarrow} M \right) \right\}_{H(X_S)} (1)$

The (1), A6 and message meaning rule infers that

$$M \models N_i | \sim \left\{ n_0, \left(N_i \stackrel{n_S^i}{\leftrightarrow} M \right) \right\} (2)$$

The A1 and freshness conjuncatenation comprehends that

$$M \models \# \left\{ n_0, \left(N_i \stackrel{n_S^*}{\leftrightarrow} M \right) \right\} \quad (3)$$

The (2), (3) and nonce verification rule deduces that $\begin{pmatrix} n_i^{i} \end{pmatrix}$

$$M \models \left\{ N_i \models n_S^i, n_0, \left(N_i \stackrel{n_S}{\leftrightarrow} M \right) \right\}$$
(4)
The (4) and believe rule inform that

The (4) and believe rule infers that

$$M \models N_i \models \left(N_i \stackrel{n_S^i}{\leftrightarrow} M\right) \quad (5)$$

From A2, (5) and jurisdiction rule, it concludes

$$M \models \left(N_i \stackrel{n_S^L}{\leftrightarrow} M\right) \tag{6}$$

This belief confirms that M has received a message from a legitimate N_i .

From M2, we have $M \le n_2$ (7) The (7) and message meaning it infers that $M \models P_i |\sim n_2$ (8)

The A2, A1, (3) and freshness conjuncatenation comprehends that

$$M \vDash \# \left\{ n_0, n_2, \left(N_i \stackrel{n_S^i}{\leftrightarrow} M \right) \right\}$$
(9)

According to nonce freshness, this proves that M confirms that N_i is recently alive and running the protocol with M.

From M3, we have

$$P_{j} \leq \left(n_{1}, n_{2}, \left(N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j}, \#\left(N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j}\right), n_{0}^{i}\right)_{K_{P}^{j}}\right)_{K_{P}^{j}}$$
(10)

The A7 and (10) deduce that

$$P_{j} \models M \mid \sim \left\{ n_{1}, n_{0}^{i}, N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j}, \# \left(N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j} \right) \right\}$$
(11)

The A3, (11) and freshness conjuncatenation comprehends that

$$P_{j} \models \# \left\{ n_{1}, n_{0}^{i}, N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j}, \# \left(N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j} \right) \right\}$$
(12)

The (11), (12) and nonce verification rule infers that

$$P_{j} \models M \models \left\{ n_{1}, n_{0}^{i}, N_{i} \stackrel{K_{s}^{l}}{\longleftrightarrow} P_{j}, \# \left(N_{i} \stackrel{K_{s}^{l}}{\longleftrightarrow} P_{j} \right), V_{i} \right\}$$
(13)

The (13) and believe rule comprehends that

$$P_j \models M \models \left(N_i \stackrel{K_S^c}{\longleftrightarrow} P_j\right)$$
 (14)

The logic belief proves that P_j is confident and believes that K_S^i is issued by M; moreover, the freshness of the key also suggests that M is alive and running the protocol with P_j and N_i .

The (13), (14) and jurisdiction rule concludes that

$$P_{j} \models \left(N_{i} \xleftarrow{K_{S}^{i}}{P_{j}}\right)$$
(15) Goal-3
From M4, we have

$$N_{i} \leq \left\{ n_{1}, N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j}, \# \left(N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j} \right), N_{i} \stackrel{n_{S}^{i}}{\leftrightarrow} M \right\}_{H(X_{S})}$$
(16)

The (16), A5 and message meaning rule comprehends that $N_i \models M \mid \sim \left\{ n_1, N_i \stackrel{K_S^i}{\longleftrightarrow} P_j, \# \left(N_i \stackrel{K_S^i}{\longleftrightarrow} P_j \right) \right\}$ (17)

The (17), A4 and freshness conjuncatenation rule infers that $N_i \models \#\left\{n_1, N_i \stackrel{K_S^i}{\longleftrightarrow} P_j, \#\left(N_i \stackrel{K_S^i}{\longleftrightarrow} P_j\right)\right\}$ (18)

The (17), (18) and nonce verification rule deduce that

$$N_{i} \models M \models \left\{ n_{1}, N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j}, \# \left(N_{i} \stackrel{K_{S}^{i}}{\longleftrightarrow} P_{j} \right) \right\}$$
(19)

The (19) and believe rule infers that

$$N_i \models M \models \left\{ N_i \stackrel{K_s^i}{\longleftrightarrow} P_j \right\}$$
(20)

The (19), (20) and jurisdiction rule concludes that

$$N_i \models \left\{ N_i \stackrel{K_S^i}{\longleftrightarrow} P_j \right\}$$
(21) Goal-1
From M5, we have

$$\begin{split} N_i &\leq IDS_j \qquad (22)\\ \text{The (15), (21), (22) and meaning rule comprehends that}\\ P_j &\models N_i \models \left\{ N_i \stackrel{K_S^i}{\longleftrightarrow} P_j \right\} \qquad (23) \text{ Goal-4}\\ \text{From M6,we have}\\ P_j &< n_1 \qquad (24)\\ \text{The (15), (21), (23) and nonce verification rule deduce that} \end{split}$$

$$N_i \models P_j \models \left\{ N_i \stackrel{K_S^i}{\longleftrightarrow} P_j \right\}$$
 (23) Goal-2

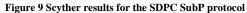
B. Verifying the protocol using the Scyther tool

The previous section proved that according to the BAN logic the SDPC is a secure authentication scheme. The Ban logic provides a foundation for the formal analysis of security protocols, but few attacks can slip through the BAN logic [11]. For further proof of the strength of the SDPC protocol suite, we implemented the SDPC in an automated security protocol analysis tool, Scyther [12]. We considered four claims: Aliveness, weak agreement, non-injective agreement, and non-injective synchronization. For a detailed description of the protocol claims, please refer to [13-14].

Parameter	Settings		
Number of Runs	1~3		
Matching Type	Find all Type Flaws		
Search pruning	Find All Attacks		
Number of pattern per claim	10		

In Scyther the protocol is modeled as an exchange of messages among different participating 'roles'; for instance, the consumer node is in the role of initiator, the publisher is in the role of responder and the subscription manger is in the role of a server. The Scyther tool integrates the authentication properties into the protocol specification as a claim event. We tested our protocol by employing the claims mentioned earlier, with the parameter settings given in Table I.

8 Scyther results : verify								
Claim				Status		Comments		
SubP	I.	SubP,12	Alive	Ok	Verified	No attacks.		
		SubP,13	Weakagree	Ok	Verified	No attacks.		
		SubP,14	Niagree	Ok	Verified	No attacks.		
		SubP,15	Nisynch	Ok	Verified	No attacks.		
	R	SubP,R1	Alive	Ok	Verified	No attacks.		
		SubP,R2	Weakagree	Ok	Verified	No attacks.		
		SubP,R3	Niagree	Ok	Verified	No attacks.		
		SubP,R4	Nisynch	Ok	Verified	No attacks.		
	S	SubP,S3	Alive	Ok	Verified	No attacks.		
		SubP,S4	Weakagree	Ok	Verified	No attacks.		
		SubP,S5	Niagree	Ok	Verified	No attacks.		
		SubP,S6	Nisynch	Ok	Verified	No attacks.		
Done								



The protocol is tested using given parameter in Table I. The results are shown in Figure 9. It is clear that SubP protocol qualifies all the protocol claims and no attacks were found. Hence, for a large number of systems and scenarios, our protocol guarantees safety against a large number of known attacks, such as impersonating, man-in-middle and replay attacks, etc.

V. CONCLUSIONS

In information-centric networking (ICN), end-to-end encryption for each subscriber makes content caching ineffective, since encrypted content stored in a cache is not useful for any other consumer except those consumers who know the encryption key. For effective caching of encrypted content, we proposed a novel scheme, called the Secure Distribution of Protected Content (SDPC). In the SDPC scheme we designed two protocol suites, the Keying Protocol suite and Subscription and Content Access Protocol suite. The Subscription and Content Access Protocol suite ensures that only authenticated consumers can access the content; hence, providing protection to content. The SDPC's keying protocol suite empowers the publisher and consumer to generate multiple symmetric encryption keys with the exchange of just a single commitment key. The commitment key is generated with the publishers' public key, along with other secret credentials, and allows the consumer to verify the originality of the published article. In other words, self-certifying is achieved with symmetric key encryption. In the conventional ICN architecture, the self-certifying is achieved by means of asymmetric cryptography, which is computationally much more expensive compared to symmetric key encryption. Hence, SDPC is a lightweight and efficient solution for the secure content distribution in ICN.

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