Formal Verification of Secure Group Communication Protocols modelled in UML

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Abstract: The paper discusses an experience in using UML and two complementary verification tools in the framework of SAFECAST, a project on secured group communication systems design. AVISPA enabled detecting and fixing security flaws. The TURTLE toolkit enabled saving development time by eliminating design solutions with inappropriate temporal parameters.

Keywords: UML, formal verification, security, real-time, group protocols.

I. INTRODUCTION

Secured group communication systems, or SGC for short, implement group management functions and communication services. The complexity level reached by SGCs has stimulated research work on dedicated modelling and formal verification techniques. The Unified Modelling Language (UML) enables system formalization and opens new avenues for formal verification of SGC models against security flaws and timing errors.

The paper shares an experience in joint application of UML and formal verification tools to SGC design. The SGC is modelled using an extended UML that contains sufficient information to derive two formal models in HLPSL (High Level Protocol Specification Language [1]) and TURTLE (Timed UML and RT-LOTOS Environment [2]), respectively. The AVISPA [1] tool uses the Dolev-Yao intruder model [3] to detect security flaws. The TURTLE toolkit, or TTool for short [4], checks TURTLE models against temporal requirements. The SGC protocol designed in the framework of SAFECAST project [5] serves as running example throughout the paper.

The paper is organized as follows. Section II defines a UML method that captures requirements using SysML requirement diagrams, and extends UML to achieve use-case driven analysis and object-oriented design. Section III introduces requirement, analysis and design patterns that apply to a broad variety of SGCs. Section IV presents the UML model of the SAFECAST SGC. The latter is hierarchically organized, and consequently members may be upgraded or downgraded. Section V addresses the *Upgrade* service and discusses the benefits of using two complementary verification tools (AVISPA and TURTLE). Section VI surveys related work. Section VII concludes the paper.

II. UML METHOD

The UML standard defines a notation, not a method. The paper promotes the use of verification-centric methods that enable early detection of design errors. The purpose is not to cover the entire design trajectory from requirement capture to maintenance, but to emphasize on the early stages of that trajectory.

A. Overview

The OMG-based UML does not provide any diagram to capture requirements. The method depicted by Figure 1 imports SysML requirement diagrams. In SysML, requirements remain informal, which hampers formal checking of design models against user or system requirements. The solution proposed for SGC design is to include logic formulas and chronograms into requirement diagrams in order to formalize security and temporal requirements, respectively.

Use-case driven analysis enables to specify the system by its boundary, the set of actors it interacts with, and the function or services it is expected to provide. Use-cases are documented by scenarios expressed in terms of sequence diagrams. Analysis diagrams contain annotations that contribute to achieve security and temporal requirement traceability.

Object-oriented design enables to model the system's architecture. An active class has a behaviour described by a state-machine which contains security and real-time information. The UML model gives sufficient information to derive HLPSL and TURTLE codes, and therefore to cater the AVISPA and TTool, respectively.

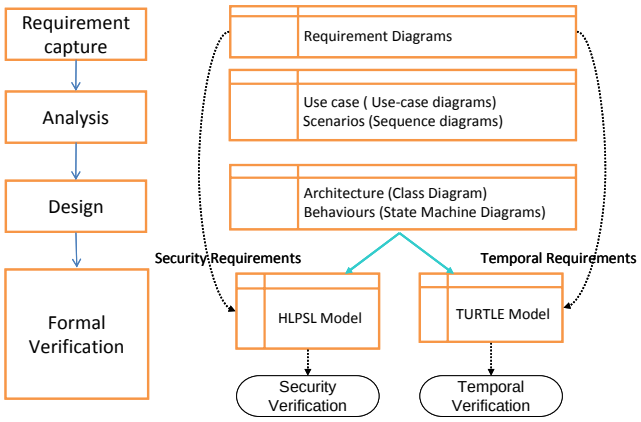

Figure 1. A UML method including formal verification

B. Security-oriented verification with AVISPA

The AVISPA [1] tool checks Internet security-sensitive protocols against security flaws. AVISPA accepts a problem specification and a property specification. Both are expressed in HLPSL, which describes each participant by a basic role and composes roles to represent scenarios. A HLPSL specification is converted to an intermediate form that is accepted by all back-ends of AVISPA. The Constraint-Logic-based Attack Searcher (CL-AtSe) backend verifies security properties, such as secrecy, authentication, fairness, and non-repudiation. Security properties may be expressed as linear logical formulas or algebraic properties. Rewriting and constraint solving techniques enable attack detection.

C. Temporal verification with TTool

TURTLE belongs to the family of real-time UML profiles that bridge the gap between the UML and formal methods worlds. The TURTLE toolkit offers a user-friendly interface to formal verification tools and supports a verification-centric method for distributed real-time system design. Formal code generators for Real-Time LOTOS (RTL), Construction and Analysis of Distributed Processes (CADP) and UPPAAL allow one to access verification techniques such as timed reachability analysis, transition system minimization and model checking of logic formulas. A Java code generator enables rapid prototyping of systems whose model includes component and deployment diagrams in addition to the requirement capture, analysis and design ones.

III. PATTERNS FOR SGCS

The benefits of using patterns have regularly been acknowledged in the literature. This section introduces patterns dedicated to a broad variety of SGCs, including situations where groups are hierarchically organized. The patterns nevertheless focus on two major functions: security algorithms that use keys and group management.

A. Requirement capture pattern

The requirement diagram pattern depicted by Figure 2 categorizes requirements in two groups (see the two <<deriveReqt>> links in the upper part of the figure). The term “general properties” denotes a set of properties that almost of systems should satisfy. Other properties are specific to the studied system. Figure 2 focuses on security and temporal requirements. For space reasons, blocks whose name ends with an “s” (e.g. *SecurityRequiments*) are not refined.

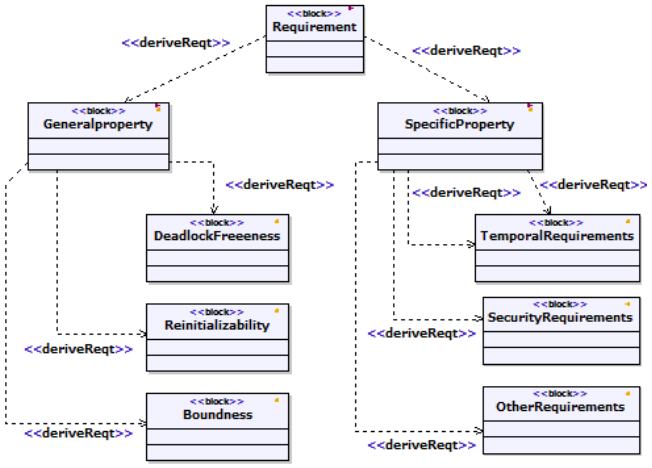

Figure 2. Requirement diagram pattern

B. Analysis pattern

SGCs commonly use security keys. The pattern in Figure 3 identifies key creation, distribution and renewal services.

SGCs also manage groups. The pattern in Figure 4 presents services that allow one person to join a group (*Join*), to leave a group upon request (*Leave*), to leave a group after an exclusion (*Exclude*), and to reenter the group (*Reinstal*).

When the group is hierarchically organized, one member moves up and down in the hierarchy using the *Upgrade* and *Downgrade* services, respectively.

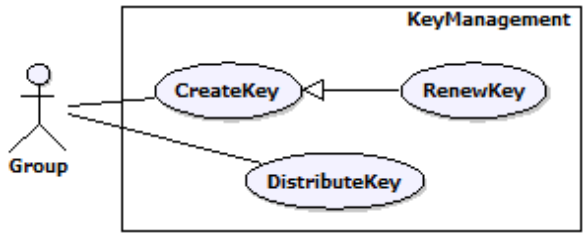

Figure 3. Analysis pattern for key management

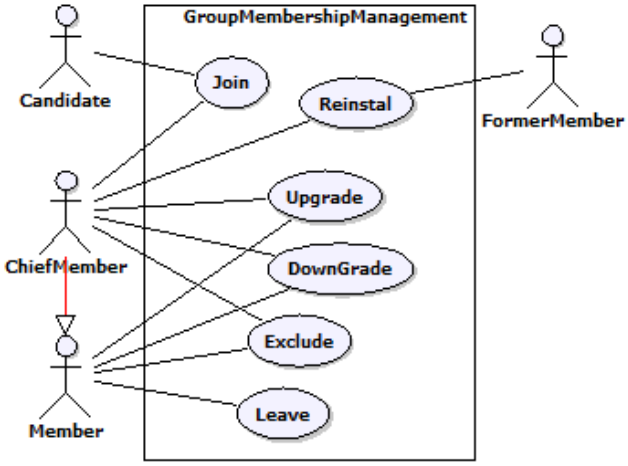

Figure 4. Pattern for group management

C. Design pattern

It is common practice in protocol design to define a 3-layer architecture where the protocol entities in the central layer rely on some pre-existing communication service to render in turn a value-added service to their upper users. The pattern in Figure 5 extends that principle to SGCs and splits the protocol layer into two sub-layers. *GMM* and *GCKM* respectively implement group management and group communication functions.

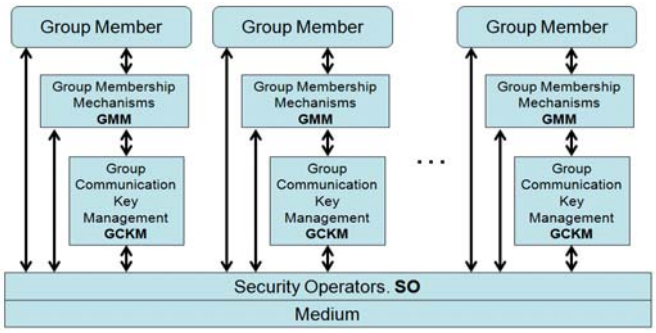

Figure 5. Architectural pattern

IV. SAFECAST SYSTEM MODELLING

A. The SAFECAST system

The secured group communication protocol designed in the framework of SAFECAST project manages hierarchically organized group of policemen, firemen and military men that work together on the same operation theatre. Each group member owns a mobile phone, and talks to others using the PMR technology (Private Mobile Radio). The protocol secures communication and manages newly created groups of Humans in a way that preserves the original hierarchies of the original groups of policemen, firemen and military men. The groups are not only hierarchical but also dynamic, since receivers may join or leave groups at any time. Last but not least, security requirements may not be dissociated from temporal ones.

B. Security and temporal requirements

Security requirements essentially address integrity and confidentiality issues (Table 1). On the other hand, temporal requirements mainly relate to maximum response delays.

	Security	Temporal
Group	- Group member authentication - Confidentiality before and after adhesion - Fighting against collusion - Node losses tolerance	- Group access delay
Interaction	- Message confidentiality before/after member adhesion/departure - Traffic encryption keys confidentiality before/after member adhesion/departure	
Communication	- Confidentiality and integrity of messages - Confidentiality and integrity of the traffic encryption keys - Message authentication - Replay avoidance	- Propagation delay - Throughput - Jitter

Table 1. Hierarchical Group Key Management Protocol requirements

C. Key management services

The use-case diagram in Figure 6 identifies several functions that achieve communication key renewal. *RenewHierarchicalKey* applies to a group whose members are hierarchically linked. The use-case includes two use-cases named *DistributeHierarchicalKey* (DHK) and *DistributePlaneKey* (DPK). DHK allows one chief to send his/her key to one group member that is responsible for his/her hierarchical level. DPK allows each responsible member to send a session key to all members belonging to its hierarchical level. DHK and DPK both use *DistributeKey*.

The keys have to be renewed on a regular basis. The diagram in Figure 6 thus contains the *RenewBasePeriodKey* use-cases.

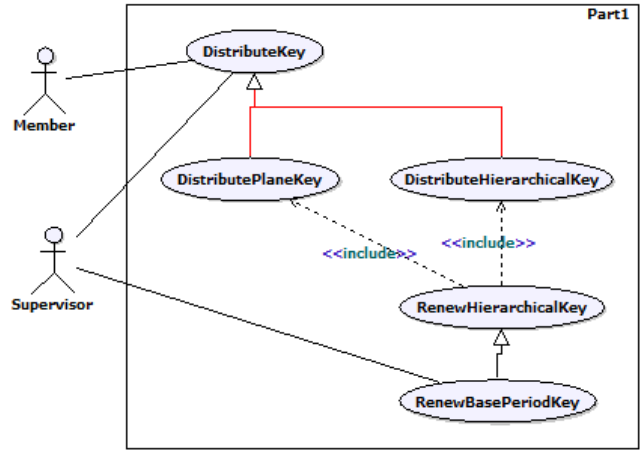

Figure 6. Security mechanism management services

D. Group management services

The use-case diagram in Figure 7 identifies a set of services that enable changes inside one group.

- *Join* and *Leave* allow one member to enter and exit a group, respectively.
- *Upgrade* and *Downgrade* services. A member has promotion when he/she moves from his/her current class *i* to an upper class *j*.
- *Reconnect* allows a member who formerly lost connection to connect again.
- *ExcludeGroupMember* manages member exclusion.
- *Reinstal* may be invoked to reinstall a previously excluded member.

All services but *ExcludeGroupMember* use the *MemberConnectionMgmt* subservice, which manages group member connections and disconnections.

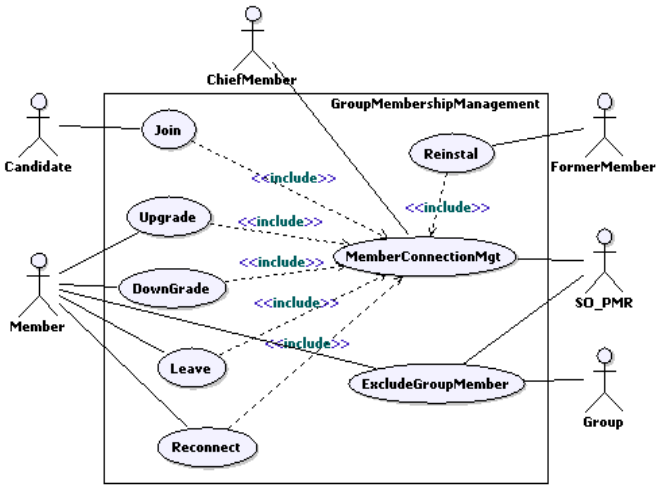

Figure 7. Services for group dynamics

The next section focuses on *Upgrade*, a service for which we identified security flaws and temporal violations.

V. UPGRADE SERVICE

A. Overview

The SAFECAST system manages a set of dynamic and hierarchical groups. The group chief is the one who decides which actions may be performed by his/her group members. Moving up in the hierarchy using the Upgrade service is an example of such actions.

B. Requirement capture

The *Upgrade* service enables a member endowed with responsibilities to leave his/her group (Figure 8) and to be replaced by another member *um* who occupied a lower position in the hierarchy. The group's administrator (not necessarily the group's chief) asks *um* to move up in the hierarchy.

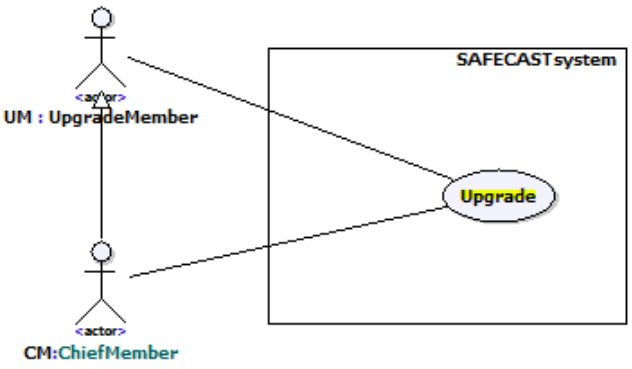

Figure 8. Use-case diagram

C. Use-case driven analysis

The *Upgrade* protocol works as follows. Member *um* issues a move-up request - including his/her Identity Certificate CI - to the chief *cm*. Depending on the validity of the attributes of *um*'s Identity certificate, *cm* decides to accept the *Upgrade* request or not. In case of acceptance, *um* receives the key of the leader's class (TEK) and a new group membership certificate (CAp), both encrypted under his or her public key pk_{um}. After successful completion, the *Upgrade* service brings the upgraded member up to an upper hierarchical level (not necessarily the closest upper level). If the upgrade request is refused, a message informs *um*, which therefore stays at the same hierarchical level. The sequence diagram in Figure 9 depicts that scenario. For the sake of clarity, only the main attributes of the certificates are represented.

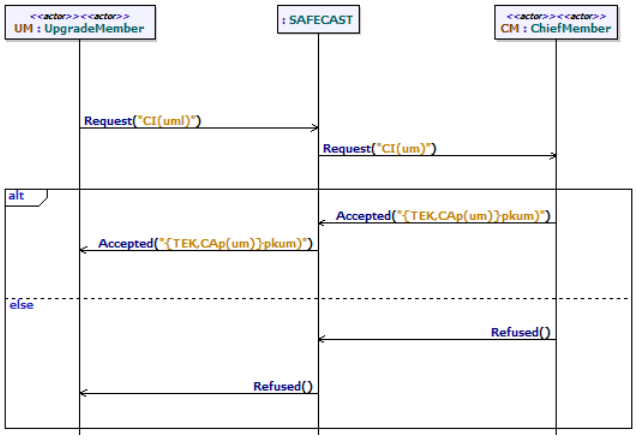

Figure 9. Sequence diagram

D. Design

The design model (Figure 10) of the SAFECAST system relies on the architectural pattern that is depicted by Figure 5.

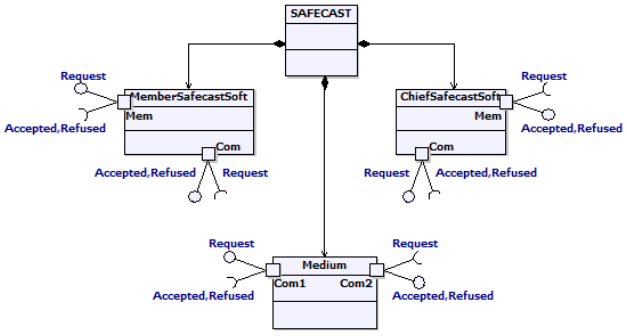

Figure 10. SAFECAST system design model

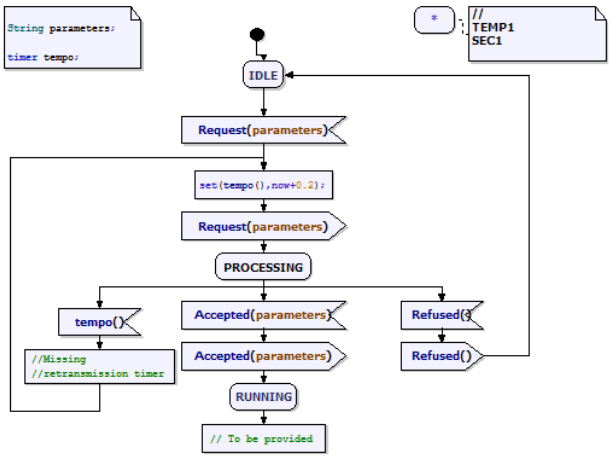

Figure 11. UpgradeMemberCom behaviour

Figure 11 depicts a fragment of the state machine used to implement the *Upgrade* service. Of particular interest are the *tempo* primitive and the security requirement starting with *secret*.

The above state machine is one among the design model elements from which formal code is derived to cater the AVISPA and TURTLE toolkits.

E. Security flaws detection using AVISPA

(1) um → cm : $SeqNum_{um}$, $\{Hash1\}pk^{-1}(um)$, CI (um)

Hash1 is the digest of the message $SeqNum_{um}$

(2) cm → um: $SeqNum_{cm}$, $\{TEK_j, CAp(um)\}pk_{um}$, $\{Hash2\}pk^{-1}(cm)$, CI (um)

Hash2 is the digest of the message $SeqNum_{cm}$, $\{TEK_j, CAp(um)\}pk_{um}$

Figure 12. AVISPA code derived from the model

A security flaw was found in the scenario attack described in Figure 12, step (1). It conforms to the “Man in the Middle” paradigm. It results from playing a single session between the *um* and *cm* members. The intruder *i* starts executing the protocol with *um*. *um* sends his/her identity certificate. The certificate is divided into an encrypted part and a part in clear. Therefore, the intruder can intercept the message and get the public key of *um*. Then, the intruder sends the intercepted message to the chief *cm* who gets the public key *pk* and uses it to encrypt the group key TEK_j as well as the new group membership certificate *CAp*. Finally, the

intruder uses the encrypting key to create a message similar to the one awaited by *um*. Also, it forces the participant *um* to take as group key any key not coming from *cm*, but composed by the intruder. None of the members is able to directly communicate with the other member, but the intruder is able to decrypt any message sent by any of them. Moreover, the intruder has the ability to become a communication relay between the two members.

The attack was fixed by adding a signature of the message (Figure 12, step (2)), using the private key of *cm*. Thus, *um* can authenticate the source of the message and extract the valid class key TEK_j. A sequence number is introduced in each message in order to avoid replay attacks.

AVISPA enabled detection of other non trivial flaws, in particular confidentiality violation. Dealing with reinstallation of a former member, AVISPA demonstrates that an intruder was able to access to information private to the group. The Reinstallation sub-protocol was fixed in [6].

F. Temporal verification using TURTLE

The reader may ask himself or herself whether the fixed version of the *Upgrade* protocol verified by AVISPA meets its expected deadlines or not. Formal verification using the TURTLE toolkit enabled comparing two configurations with a low-rate PMR at 6 kb/s with a 3 kms range and an average-rate PMR at 100 kb/s value with a 100 kms range, respectively.

Formal verification identified four temporal requirements met for an average-rate PMR (Table 2), but unmet for a low-rate PMR. A concrete benefit of formal verification using the TURTLE toolkit was to save development time: it was decided to not develop the SAFECAST SGC over a low-rate PMR.

For the middle-rate PMR network, all the services verified using TURTLE meet the requirements of middle-rate PMR network, but the *Downgrade* and *Reinstall* services. Duration of 490 ms was computed for the two services, which exceeds the 350 ms limit required for the “accessing to multimedia groups.” In order not to sacrifice the entire security procedure, it was decided to relax the “accessing to multimedia groups” requirement to 500 ms.

Requirement	Limit duration (ms)	Upgrade protocol on average-rate network (Execution time 331 ms)
Detecting an integrity violation	10 000	Widely validated
Detecting a replay	10 000	Widely validated
Accessing to a multimedia group	350	Shortly validated
Accessing to textual message groups	60 000	Very widely validated

Table 2. Temporal requirements and computed time for the Upgrade service

VI. RELATED WORK

A. Formal automated security verification of group protocols

The benefits of applying formal verification to security protocols have first been acknowledged for two- and three-party protocols. Nowadays, group protocols raise much more complex security problems [7] [8] [9] [10] since they involve an unbounded number of participants and consider some complicated security properties. Significant attacks on such protocols have been found using automated techniques.

Taghdir and Jackson [9] modelled the multicast group key management protocol proposed by Tanaka and Sato [11]. They exhibited several properties not satisfied by the protocol and proposed an “improved” protocol whose model did not include any active attacker. Steel and Bundy [12] identified serious attacks in the so-called “improved” protocol. They used CORAL, a tool also used to discover attacks on the Asokan-Ginzboorg and Iolus [13] protocols.

Work on group protocol verification systematically raises an infinite search space problem since even one legal execution of the protocol requires an unlimited number of steps. Meadows and Syverson [14] extended the NRL protocol analyzer in order to tackle the GDOI's protocols [8].

Several tools primarily designed for attack search have been extended to handle group protocols. Examples include algebraic primitives (e.g. XOR) and the exponentiation often encountered in extensions of key agreement based upon

Diffie-Hellman. CL-AtSe, one of the four back-ends used in AVISPA [1], is an example addressed in this paper.

Tools for protocol falsification (searching for attacks) have been extended to handle group protocols and to cope with additional requirements, such as algebraic primitives and exponentiation (regularly encountered in extensions of Diffie-Hellman-based key agreement). These tools include CL-AtSe. Modular by its extensibility to new classes of protocols or requirements, and powerful by the number of protocol sessions that it can deal with, the tool has been applied to a large number of Internet security protocols.

Other tools extensions are due to the fact that most group protocols include algebraic properties (xor, exponentiation). To our knowledge, CL-AtSe is the only tool for protocol analysis that simultaneously offers complete unification algorithms for xor and exponentiation and does not limit either terms or intruder operations.

Apart from algebraic requirements, group protocols guarantee security properties that do not limit to secrecy or authentication properties. Unlike tools that exclusively verify these two properties, CL-AtSe can verify any state-based security property. Besides secrecy and authentication, it indeed verifies additional properties such as fairness and non-repudiation.

B. Temporal requirements and verification of SGC systems

Research papers that identified security flaws in SGC systems mostly address security functions without taking temporal constraints into account. Corin et al. [15] demonstrated that protocols with secret exchanges that had been proven robust and secure by time-independent analysis may be no longer robust as soon as time is explicitly taken into account.

With the exponential growth of wireless networks [16], ad-hoc networks [17] [18] and peer to peer technology, SGC have become an extremely important and active research area. The complexity in these SGC stems from the addition of security and temporal requirement to the dynamic evolution of the groups.

Isis [19] [20], RMP [21], Transis [22], Horus/Ensemble [20] and Totem [23] were the first communication systems developed with distributed group management in mind. They offer programmers a flexible group communication model and group protocols stacks. Auto-configuration was introduced in Renesse et al. [24]. Other

improvements include auto-adaptation, integrated security, real-time and fault-tolerance mechanisms. Bimodal-Multicast (Gossip-based protocols) [19] and Springlass systems (Ensemble follow-up) include new reliability, authentication and delivery services to improve scalability and stability of secure group communication systems. Evaluation and failure identification were proposed for these approaches, based on formal analysis.

Group communication systems with security services were introduced at the network level by the Enclave project [25] and at the middleware level by the Cactus environment [26]. Another avenue was opened by policy-based systems. For instance, the Antigone system [27] uses policies to address membership capabilities (e.g. control access) and security requirements (e.g. data confidentiality, integrity and authentication).

Other recently published work simultaneously addresses temporal requirements and security constraints. Spread [23] is a group communication platform which offers an integrated and secure architecture for distributed client-server systems. Group communications are enhanced with security services without sacrificing the robustness and performance of the system. Spread's layered architecture is based on dedicated servers implementing security services. Almeida [28] proposes a set of group communication protocols to satisfy real-time and dependability requirements, despite of some difficulties introduced by the groups' dynamicity. Three different Quality of Service properties are guaranteed: timeliness, order and agreement. Gutierrez-Nolasco et al. [29] also explore two adaptability issues - namely security and synchrony of group communications systems (GCS) - to maintain a consistent view of dynamic groups.

C. UML modelling of SGC systems

UML standards and extensions are of great help for proposing methodological approaches that embed temporal and security requirements during the system design processes.

In [30], Jürjens et al. apply a UML profile (UMLsec) to a mobile communication system. The authors use analysis, design and deployment diagrams. The system is verified against security flaws. In the paper, we propose a method centred on requirement capture, analysis and design. The deployment phase is not addressed. We map UML models into their corresponding formal representations for

automated verification using TURTLE and AVISPA. The result is that we check the security and temporal properties of the model correspondingly. This joint use of two formal verification tools enabled eliminating design solutions that passed security tests but did not meet the deadlines.

Like Jürjens et al. [30], Morimoto et al. [31], Abie et al. [32] and Woodside et al. [33] extend UML with security-centric constructs. Morimoto et al. [31] promotes the use of patterns. In practice they detail an "authentication pattern" and its translation to Z, a formal language which enables formal verification. The patterns proposed in this paper are more general and take group management functions into account.

Woodside et al. [33] discusses performances issues and therefore opens a new avenue for security modelling in UML. To evaluate performance and scalability, the SAFECAST project used an approach based on simulation with the NS[1] tool.

VII. CONCLUSIONS

Secure group communication systems capture complex design problems in terms of group management, security flaws and temporal violations detection. Some SGC, in particular the SAFECAST system discussed in the paper, further manage hierarchically organized groups. The design of such systems therefore deserves research investigations in rigorous development methodologies based on modelling techniques and formal verification tools.

The paper proposes a UML method which covers the requirement capture, analysis and design steps of the design trajectory of SGCs. The requirement, analysis and design steps use an annotated UML to take security and temporal requirements into account. Formal codes amenable to the AVISPA and TURTLE toolkits are derived from the design models in UML. They enable early checking of design models against security and temporal requirements. AVISPA and TURTLE remain separate and so each tool explores the system's state space separately. Work has still to be done for discovering problems where security and timing cannot be verified in sequence but in parallel.

The proposed method was applied to the SAFECAST system. The latter was checked against security flaws and temporal requirements. Several security flaws were detected with AVISPA. The problems have been fixed and the group

communication protocol is now more secure. On the other hand, the system was investigated with two PMR radios, termed as ‘low-rate’ and ‘medium-rate’ PMR radios. The TURTLE toolkit proved that most temporal requirements are satisfied by the version based on the medium-rate PMR. Conversely, the configuration using a low-rate PMR violates important temporal requirements. It was decided to not develop it.

The approach proposed in the paper is not restricted to the SAFECAST SGC. Indeed, we plan to apply our approach to validate the applicability of others communication architectures, such as an audio-video multicast streaming application within ad hoc networks. This kind of applications requires a high level of security, in addition to the real-time requirements, to offer the best possible quality of service, within constrained environment.

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