A More Realistic Model for Verifying Route Validity in Ad-Hoc Networks: Corrected Version

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Abstract. Many cryptographic protocols aim at ensuring the *route validity* in ad-hoc networks, *i.e.* the established route representing an exists path in the network. However, flaws have been found in some protocols that are claimed secure (*e.g.* the attack on SRP applied to DSR). Some formal models and reduction proofs have been proposed to give more guarantees when verifying route validity and facilitate verification process. The existing approaches assume the cooperative attacker model. In this paper, we consider the non-cooperative attacker model, and we show that verifying the route validity under the non-cooperative model requires to verify only five topologies, each containing four nodes, and to consider only three malicious (compromised) nodes. Furthermore, we prove that a protocol is secure for any topology under the non-cooperative model, if and only if, it is secure for any topology under the cooperative model.

Keywords: Routing protocols, non-cooperative attacker, route validity, reduction proof.

1 Introduction

Wireless ad-hoc networks have no existing infrastructure. This enables them to play more and more important role in extending the coverage of traditional wireless infrastructure (*e.g.* cellular networks, wireless LAN, etc.). These networks have no central administration control, and thus the presence of dynamic and adaptive routing protocols is necessary for them to work properly. Routing protocols aim to establish a route between distant nodes, enabling wireless nodes to communicate with the nodes that are outside their transmission range. Attacking routing protocol may disable the whole network operation. For example, forcing two nodes to believe in an invalid route (a path that is not in the network) will prevent them from communicating with each other. Several routing

* The possible topology $\mathcal{T}'$ in Lemma 3 has been modified by adding an additional node to it. Moreover, some sentences have been rephrased without any change to their meaning. Thanks to Véronique Cortier and Stéphanie Delaune.

protocols [PH02,HPJ05,SDL+02] have been proposed to provide more guarantees on the resulting routes for ad-hoc networks. However, they may be still subject to attacks. For example, a flaw has been discovered on the Secure Routing Protocol SRP [PH02] when it applied to Dynamic Source Routing protocol DSR [JMB01], allowing an attacker to modify the route, which makes the source node accept an invalid one [BV04]. Another attack was found on the Ariadne protocol [HPJ05] in the same paper. This shows that designing secure routing protocol is a difficult and error-prone task. An NP-decision procedure has been proposed by M. Arnaud *et al.* [ACD10] for analysing routing protocols looking for attacks on route validity in case of a fixed topology. However, the existence of an attack strongly depends on the network topology, *i.e.* how nodes are connected and where malicious nodes are located. This results in an infinite number of topologies to verify, which is not tractable. Indeed, in contrast to classical Dolev-Yao attacker [DY83] that controls all the communications, an attacker for routing protocols has to situate somewhere in the network. It can control only a finite number of nodes (typically one or two), and thus it can listen to the communication of its neighbours but it is not possible to listen beyond the neighbouring nodes. Cortier *et al.* [CDD12] proposed a reduction proof when looking for route validity property under the *cooperative attacker model*, *i.e.* a model that allows distant malicious nodes to communicate using out-of-band resources, and thus to share their knowledge.

In fact, due to their minimal configuration and quick deployment ad-hoc networks are suitable for emergency situations like natural disasters or military conflicts where no infrastructure is available. So, usually it is difficult to have common channels between malicious nodes. As an example, consider the case of ad-hoc sensors that are thrown from a plane into the enemy field during a battle. Also, in-band-communications between malicious nodes are unfeasible in some cases where nodes have low power capabilities (*e.g.* sensor networks). Moreover, it is well-known that the presence of several colluding malicious nodes often yields straightforward attacks [cHPJ06,LPM+05].

Contributions: We consider route validity property under the *non-cooperative* attacker model, where malicious nodes work independently, *i.e.* they have no ability to share their knowledge. We use the CBS♯ [NH06] calculus to model routing protocol, and the transition rules introduced in [ACD10] to model the communications between nodes, after updating them to handle the behaviour of the non-cooperative malicious nodes instead of the cooperative ones.

Then, we revisit the work presented by Cortier *et al.* in [CDD12], where they show that when looking for attacks on route validity under the cooperative model it is enough to check only five particular small topologies. We show that the same result is also valid in case the of non-cooperative model: first, we show that if there is an attack on a routing protocol in a certain topology under the non-cooperative model, then there is an attack on this protocol in a smaller topology obtained from the original one by a simple reduction. Then, we show that applying the reduction procedure to any topology leads to (at most) five

small topologies. The resulting topologies are the same ones obtained in [CDD12] under the cooperative model.

Finally, we prove that a protocol is secure under the cooperative model in any topology, if and only if, it is secure under the non-cooperative model in any topology. The latter result does not hold when we consider only one fixed topology.

Related work: The non-cooperative model is already used in [ACRT11] to analyse the web-service applications looking for attacks that exploit XML format. Verifying route validity under this model is equivalent to satisfiability of general constraints where knowledge monotonicity does not hold. The satisfiability of such kind of constraints has been proven to be NP-complete [Maz05,ACRT11]. However, verifying routing protocols requires considering an infinite number of topologies as we mentioned before.

Andel *et al.* [ABY11] have proposed an approach to automatically detect attacks against route validity of ad-hoc routing protocols. The authors have also proposed a symmetric-based network reduction techniques in order to reduce the computational times. Nevertheless still there are too many possible network topologies even for a fixed number of nodes.

Cortier *et al.* [CDD12] have shown that only five topologies need to be considered when looking for attacks on properties such as route validity under the cooperative model. In this paper, we follow the spirit of their work. Our work differs by considering the non-cooperative model which is a weaker one. We show that the problem of checking if a certain protocol is secure for any topology is equivalent under the two models. However, in a fixed topology we may find a protocol that is secure under the non-cooperative model, but not under the cooperative one. Actually, considering a powerful attacker model by giving malicious nodes the ability to share their knowledge may introduce some false positive attacks in the sense that we may found some attacks that can not be to mounted in practice. Also, we should note that studying protocol security under the non-cooperative model requires strictly less executions to be considered.

Outline: We introduce notations and attacker capabilities in Section 2. Then in Section 3, we show how to model routing protocols by process calculus, and we define the security property. In Section 4, we present our reduction proof and show that only five topologies are sufficient. Finally, before concluding, we make a comparison between the cooperative and non-cooperative models in Section 5.

2 Preliminaries

To model messages we consider an arbitrary term algebra and deduction system.

2.1 Messages

We use *terms* to represent messages and *function symbols* to represent cryptographic primitives such as encryption and hash function. We consider a *signature*

$(\Sigma, \mathbb{S})$ made of a set of sorts $\mathbb{S}$ and a set of function symbols Σ with *arities*, $ar(\cdot) : \Sigma \mapsto \mathbb{N}$. The set of function symbols of arity n is denoted by Σ_n. For a function symbol $f \in \Sigma_n$ we have that $f : s_1 \times \cdots \times s_n \mapsto s$ with $s, s_1, \ldots, s_n \in \mathbb{S}$. We consider a countable set of variables $\mathbb{X}$. For a set $X \subseteq \mathbb{X}$, we define a set of terms $\mathbb{T}(\Sigma, X)$ to be the smallest set containing Σ_0 and X, such that for a function symbol $g \in \Sigma_n$: if $t_1, \ldots, t_n \in \mathbb{T}(\Sigma, X)$ then $g(t_1, \ldots, t_n) \in \mathbb{T}(\Sigma, X)$. In the case that $X = \emptyset$, we simply write $\mathbb{T}(\Sigma)$, this is the set of ground terms.

We assume two special sorts: the sort Agent that only contains agent's names and variables, and the sort Term that subsumes all other sorts so that any term is of the sort Term. As an example, a typical signature for representing the primitives used in SRP [PH02] protocol is the signature $(\Sigma_{SRP}, \mathbb{S}_{SRP})$ defined by $\mathbb{S}_{SRP} = \{\mathsf{Agent}, \mathsf{List}, \mathsf{Term}\}$ and $\Sigma_{SRP} = \{hmac.(\cdot), \langle \cdot, \cdot \rangle, ::, [], req, rep\}$, where req and rep are unitary constants identify the request and response phases respectively, [] represents an empty list and other symbols are defined as follows:

$$\langle \cdot, \cdot \rangle \ : \mathsf{Term} \times \mathsf{Term} \to \mathsf{Term} \qquad :: \ : \mathsf{Agent} \times \mathsf{List} \to \mathsf{List}$$
$$hmac.(\cdot) \ : \mathsf{Term} \times \mathsf{Term} \to \mathsf{Term}$$

The symbol $hmac.(\cdot)$ takes two terms and computes the message authentication code MAC of the first term with the second one as a key. The operator $\langle \cdot, \cdot \rangle$ produces a concatenation of two terms, and the operator :: is the list constructor. We write $<t_1, t_2, t_3>$ for the term $\langle \langle t_1, t_2 \rangle, t_3 \rangle$, and $[t_1, t_2, t_3]$ for $(([] :: t_1) :: t_2) :: t_3$.

Substitutions and unifications: A *substitution* σ is a mapping from $\mathbb{X}$ to $\mathbb{T}(\Sigma, \mathbb{X})$ with the domain $dom(\sigma) = \{x \in \mathbb{X} \mid \sigma(x) \neq x\}$. We consider only *well-sorted substitutions*, that is substitution for which x and $\sigma(x)$ have the same sort. We extend σ to a homomorphism on functions, processes and terms as expected. We say that the two terms t and s are *unifiable* if there exists a substitution θ, called *unifier*, such that $\theta(t) = \theta(s)$. We define the *most general unifier* (for short *mgu*) of two terms t and s to be a unifier, denoted $mgu(t, s)$, such that for any unifier θ of t and s there exists a substitution σ with $\theta = \sigma \circ mgu(t, s)$ where $\circ$ is a composition of two mappings. We write $mgu(t, s) = \perp$ when t and s are not unifiable.

2.2 Attacker Capabilities

We consider a non-cooperative model where there are multiple independent attackers that have no ability to share knowledge between each other. Each attacker can deduce new messages from messages that he has initially and has observed by eavesdropping. The deduction capabilities of an attacker are defined using a deduction system similar to the one given below. We denote by $T \vdash t$ the fact that the term t is deducible from the set of terms T.

We can associate to the SRP signature $(\Sigma_{SRP}, \mathbb{S}_{SRP})$, the following deduction system:

$$\frac{t_1 \quad t_2}{\langle t_1, t_2 \rangle} \qquad \frac{\langle t_1, t_2 \rangle}{t_i} \ i \in \{1, 2\} \qquad \frac{l_1 \quad l_2}{l_1 :: l_2} \qquad \frac{l_1 :: l_2}{l_i} \ i \in \{1, 2\} \qquad \frac{t_1 \quad t_2}{hmac_{t_2}(t_1)}$$

The terms t_1 and t_2 are of sort Term, l_1 is of sort List, whereas l_2 is of sort Agent. The rule $\dfrac{t_1 \quad t_n}{t}$ means that an attacker can derive the term t from the terms $t_1, \ldots, t_n$. Thus, the system above gives the attacker the ability to concatenate terms, build lists, as well as to retrieve their components. The last inference rule models the fact that the attacker can also compute a MAC provided he knows the corresponding key.

3 Modelling Routing Protocols

3.1 Process Calculus

The intended behaviour of each node in the network can be modelled by a process defined using the grammar given in Figure 1. We use the CBS♯ calculus introduced in [NH06]. We parameterized them by a set $\mathbf{P}$ of predicates to represent the checks performed by the agents, and a set $\mathcal{F}$ of functions over terms to represent the computations performed by the agents. The set of functions $\mathcal{F}$ contains functions that are more complex than basic cryptographic primitives represented by Σ, for example a function $f : (x, y, z) \mapsto hmac_z(\langle x, y \rangle)$ which takes three terms, concatenates the first two and then computes the MAC over them with the third term. They can also be used to model operations on lists, for example we can define a function that take a list and return its reverse.

$P, Q ::=$	Processes
0	null process.
$out(f(t_1, \ldots, t_n)).P$	emission
$in(t).P$	reception
$if\ \Phi\ then\ P$	conditional
$P \mid Q$	parallel composition.
$!P$	replication
$new\ m.P$	fresh name generation

where $t, t_1, \ldots, t_n$ are terms, m is a name, $f \in \mathcal{F}$ and Φ is a formula:

$\Phi, \Phi_1, \Phi_2 ::=$	Formula
$p(t'_1, \ldots, t'_n)$	$p \in \mathbf{P}$, $t'_1, \ldots, t'_n$ are terms
$\Phi_1 \wedge \Phi_2$	conjunction

Fig. 1. Process grammar

The process $out(f(t_1, \ldots, t_n)).P$ first computes the term $t = f(t_1, \ldots, t_n)$, emits t, and then behaves like P. The reception process $in(t).P$ expects a message m matching the pattern t and then behaves like $\sigma(P)$ where $\sigma = mgu(m, t)$. The process $if\ \Phi\ then\ P$ tests whether Φ is true, if Φ is true it then behaves like P. Two processes P and Q running in parallel represented by the process $P|Q$. The

replication process $!P$ denotes an infinite number of copies of P, all running in parallel. The process $new\ m.P$ creates a fresh name m and then behaves like P. Sometimes, for the sake of clarity we omit the null process. We assume that the predicates $p \in \mathbf{P}$ are given together with their semantics that may depend on the underlying graph G. We consider two kinds of predicates: a set $\mathbf{P_I}$ of predicates whose semantics is independent of the graph and a set $\mathbf{P_D}$ of predicates whose semantics is dependent on the graph. For a graph dependent formula Φ and a graph G, we write $[\![\Phi]\!]_G = true$ (resp. $false$) to denote that Φ is $true$ (resp. $false$) in G. For example, we can use the predicates $\mathbf{P_{SRP}} = \mathbf{P_I} \cup \mathbf{P_D}$ for SRP, with $\mathbf{P_I} = \{\mathsf{checksrc}, \mathsf{checkdest}\}$ and $\mathbf{P_D} = \{\mathsf{check}, \mathsf{checkl}\}$. The purpose of the $\mathbf{P_I}$ predicates is to model some checks that are performed by the source when it receives the route. The semantics of these predicates is defined as follows:

- $\mathsf{checksrc}(S, l) = true$ if and only if l is of sort List and its first element is S,
- $\mathsf{checkdest}(D, l) = true$ if and only if l is of sort List and its last element is D.

The predicates $\mathsf{checksrc}(S, l)$ and $\mathsf{checkdest}(D, l)$ are used by the source process to verify that the first and last nodes of the established route are the source and destination of the route discovery respectively.

While, the purpose of the $\mathbf{P_D}$ predicates is to model neighbourhood checks. Given a graph $G = (V, E)$, their semantics is defined as follows:

- $[\![\mathsf{check}(A, B)]\!]_G = true$ if and only if $(A, B) \in E$ or $(B, A) \in E$,
- $[\![\mathsf{checkl}(C, l)]\!]_G = true$ if and only if C appears in l and for any l' subterm of l we have $(A, C) \in E$ if $l' = l_1 :: A :: C$ and $(C, B) \in E$ if $l' = l_1 :: C :: B$.

The aim of the predicate $[\![\mathsf{check}(A, B)]\!]_G$ is to check if A and B are neighbours in G, while the aim of the predicate $[\![\mathsf{checkl}(C, l)]\!]_G$ is to check if the node C appears in l between two neighbours in G. We assume that each nodes knows its neighbours in the network, this can be achieved by running a certain neighbour discovery protocol in advance.

We write $fv(P)$ for the set of *free variables* that occur in P, *i.e.* the set of variables that are not in the scope of an input. We consider ground processes, *i.e.* processes P such that $fv(P) = \emptyset$, and parameterized processes, denoted $P(x_1, \ldots, x_n)$ where $x_1, \ldots, x_n$ are variables of sort Agent, and such that $fv(P) \subseteq \{x_1, \ldots, x_n\}$. A routing role is a parameterized process that does not contain any name of sort Agent. A routing protocol is then simply a set of routing roles.

The secure routing protocol SRP applied on DSR, already modelled in [CDD12] using these process calculus. Here we give only the source process as an example. Considering the signature $(\Sigma_{SRP}, \mathbb{S}_{SRP})$ and the predicates $\mathbf{P_{SRP}}$ introduced before, and the set $\mathcal{F}_{SRP}$ of functions over terms that only contains the identity function (omitted for sake of clarity), the process played by the source x_S initiating the search of a route towards a destination x_D is given as follows:

$$P_{src}(x_S, x_D) = \text{new } id.out(u_1).in(u_2).\text{if } \Phi_S \text{ then } 0$$

where id is a constant identifies the request, x_S, x_D are variables of sort Agent, and x_L is a variable of sort List and

$$u_1 = \langle req, x_S, x_D, id, [] :: x_S, hmac_{k_{x_S x_D}}(\langle req, x_S, x_D, id\rangle)\rangle$$
$$u_2 = \langle req, x_D, x_S, id, x_L, hmac_{k_{x_S x_D}}(\langle req, x_D, x_S, id, x_L\rangle)\rangle$$
$$\Phi_S = \mathsf{checkl}(x_S, x_L) \wedge \mathsf{checksrc}(x_S, x_L) \wedge \mathsf{checkdest}(x_D, x_L)$$

3.2 Configuration and Topology

In the classical Dolev-Yao model [DY83], the attacker controls all the communication channels. It is not the case with ad-hoc networks where the attacker has to be located at a specific node, and thus can only interact with its neighbours. Similarly to [CDD12], we represent a network *topology* by a tuple $\mathcal{T} = (G, \mathcal{M}, S, D)$ where:

- $G = (V, E)$ is an undirected graph. The set $V \subseteq \{A \in \Sigma_0 \mid A \text{ of sort } \mathsf{Agent}\}$ represents the set of network nodes. An edge (A, B) in E means that the two nodes A and B are neighbours. We assume that a node can receive messages that it sent, that is for any $A \in V$, we have that $(A, A) \in E$;
- $\mathcal{M} = \{M_i\}_{i=1}^{i=k}$ is a set of nodes that are controlled by k independent attackers we have in the network, where each attacker controls only one node. Note that $\mathcal{M} \subseteq V$. These nodes that are in $\mathcal{M}$ are called malicious whereas nodes not in $\mathcal{M}$ are called honest;
- S and D are respectively the source and the destination nodes of the routing protocol run. We assume that S and D are always honest.

Note that malicious nodes cannot communicate using out-of-band resources or hidden channels.

Again similar to [CDD12], we define a *configuration* of the network with graph (V, E) using a pair $(\mathcal{P}, \mathcal{I})$ where:

- $\mathcal{P} = \{\lfloor P \rfloor_A \text{ for some } A \in V\}$ is a multiset with $\lfloor P \rfloor_A$ represents the process P that is executed by the node A. In the following, we may write $\lfloor P \rfloor_A$ instead of $\{\lfloor P \rfloor_A\}$;
- We assume an independent knowledge for each attacker as we define the set of sets of terms $\mathcal{I} = \{I_i\}_{i=1}^{i=k}$, where the set I_i represents the messages that the malicious node $M_i \in \mathcal{M}$ has initially and also that it has observed on the network.

A possible topology $\mathcal{T}_0 = (G_0, \mathcal{M}_0, S, D)$ is modelled in Figure 2, where M_1 and M_2 are malicious nodes (colored in black), *i.e.* $\mathcal{M}_0 = \{M_1, M_2\}$ while A is an extra honest node (colored in white). To refer to the source and destination we use and  respectively. A typical initial configuration for the SRP protocol is

$$K = (\lfloor P_{src}(S, D) \rfloor_S \mid \lfloor P_{req}(A) \rfloor_A \mid \lfloor P_{rep}(A) \rfloor_A \mid \lfloor P_{dest}(D) \rfloor_D; \mathcal{I})$$

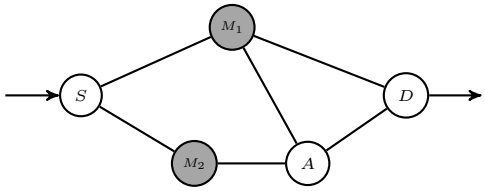


Fig. 2. Topology $\mathcal{T}_0$

3.3 Execution Model

Figure 3 presents the set of communication rules for a given topology $\mathcal{T} = (G, \mathcal{M}, S, D)$ with $G = (V, E)$. They are similar to those used in [ACD10,CDD12] with the difference that we use an independent attackers knowledge, and we assume that the message sent by a certain malicious node can be captured by its malicious neighbours due to broadcast nature of the communications in wireless add-hoc networks, this modelled in the rule IN. Thanks to COMM rule, neighbour nodes can exchange messages between each others. When a node sent a message, it is added to the knowledge I_i if this node is a neighbour of M_i. A malicious node M_i is provided the capability to send any message, it can build from its knowledge I_i, to one of its neighbours. This is modeled using IN rule. Note that, like in case of COMM rule the sent message is captured by neighbour malicious nodes. The rule IF-THEN states that the node A executes the process P only if the formula Φ is true. PAR rule says that parallel processes are equivalent to parallel nodes running these processes. The replication process $!P$ expanded using the rule REPL. The last rule NEW says that nodes can use fresh names of their choice when required. The relation $\rightarrow_{\mathcal{T}}^{*}$ is the reflexive and transitive closure of $\rightarrow_{\mathcal{T}}$.

3.4 Security Property

We consider the route validity property. We say that a protocol satisfies route validity property and thus secure if it results in a *valid route*. In the follows, we present what is the valid route and what is the attack on a routing protocol.

Definition 1 (Valid route [CDD12]). *Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$. We say that a list $l = [A_1, \ldots, A_n]$ of agent names is a valid route in $\mathcal{T}$, if and only if, for any $i \in \{1, \ldots, n-1\}$, $(A_i, A_{i+1}) \in E$ or $A_i, A_{i+1} \in \mathcal{M}$.*

We do not consider the case of wormhole attack where we have two successive non-neighbour malicious nodes.

Similarly to [CDD12], we assume that an instance of a routing protocol contains a process that outputs the term $end(l)$ when the route, represented by list l, is established. This allows us to represent the route validity property as a reachability property.

The attack on the configuration of a routing protocol can be modelled by the following definition.

COMM $(\{\lfloor in(t'_j).P_j \rfloor_{A_j} \mid mgu(t,t'_j) \neq \bot, (A,A_j) \in E\}$
$\cup \lfloor out(f(t_1,\ldots,t_n).P \rfloor_A \cup \mathcal{P}; \mathcal{I}) \rightarrow_{\mathcal{T}} (\lfloor P_j\sigma_j \rfloor_{A_j} \cup \lfloor P \rfloor_A \cup \mathcal{P}; \mathcal{I}')$,
where $\sigma_j = mgu(t,t'_j)$ with $t = f(t_1,\ldots,t_n)$, and for $i \in \{1,\ldots,k\}$, if $(A,M_i) \in E$, then $I'_i = I_i \cup \{t\}$, else $I'_i = I_i$.

IN $(\lfloor in(t').P \rfloor_A \cup \mathcal{P}; \mathcal{I}) \rightarrow_{\mathcal{T}} (\lfloor P\sigma \rfloor_A \cup \mathcal{P}; \mathcal{I}')$, if $(A,M_j) \in E$, $I_j \vdash t$ & $M_j \in \mathcal{M}$
where $\sigma = mgu(t,t')$, and if $(M_j,M_i) \in E$ $I'_i = I_i \cup \{t\}$, else $I'_i = I_i$.

IF-THEN $(\lfloor \text{if } \Phi \text{ then } P \rfloor_A \cup \mathcal{P}; \mathcal{I}) \rightarrow_{\mathcal{T}} (\lfloor P \rfloor_A \cup \mathcal{P}; \mathcal{I})$, if $[\![\Phi]\!]_G = 1$.

PAR $(\lfloor P_1|P_2 \rfloor_A \cup \mathcal{P}; \mathcal{I}) \rightarrow_{\mathcal{T}} (\lfloor P_1 \rfloor_A \cup \lfloor P_2 \rfloor_A \cup \mathcal{P}; \mathcal{I})$

REPL $(\lfloor !P \rfloor_A \cup \mathcal{P}; \mathcal{I}) \rightarrow_{\mathcal{T}} (\lfloor P \rfloor_A \cup \lfloor !P \rfloor_A \cup \mathcal{P}; \mathcal{I})$

NEW $(\lfloor new\ m.P \rfloor_A \cup \mathcal{P}; \mathcal{I}) \rightarrow_{\mathcal{T}} (\lfloor P\{m \mapsto m'\} \rfloor_A \cup \mathcal{P}; \mathcal{I})$,
where m' is a fresh name.

Fig. 3. Transition system.

Definition 2 (Attack on a configuration K in $\mathcal{T}$ [CDD12]). *Let $\mathcal{T} = (G,\mathcal{M},S,D)$ be a topology and K be a configuration. We say that K admits an* attack *in $\mathcal{T}$ if $K \rightarrow^*_{\mathcal{T}} (\lfloor out(end(l)).P \rfloor_A \cup \mathcal{P}; \mathcal{I})$ for some A, P, $\mathcal{P}$, $\mathcal{I}$, and some term l that is not a valid route in $\mathcal{T}$.*

To reason about a routing protocol $\mathcal{P}_{routing}$, we consider configurations that are valid for $\mathcal{P}_{routing}$. Similarly to [CDD12], we define valid configuration as follows.

Definition 3 (Valid configuration). *Let $\mathcal{P}_{routing}$ be a routing protocol, and P_0 be a routing role. Let $\mathcal{T} = (G,\mathcal{M},S,D)$ be a topology with $G = (V,E)$, and $\mathcal{I}$ be a set of sets representing the initial knowledge of the malicious nodes in $\mathcal{M}$. A configuration $K = (\mathcal{P},\mathcal{I})$ is valid for $\mathcal{P}_{routing}$ and P_0 with respect to $\mathcal{T}$ and $\mathcal{I}$ if*

- *$\mathcal{P}$ is of the form $\lfloor P_0(S,D) \rfloor_S \uplus \mathcal{P}'$; and*
- *For every $\lfloor P' \rfloor_{A_1} \in \mathcal{P}'$, we have that $P' = P(A_1,\ldots,A_n)$ for some process $P(x_1,\ldots,x_n) \in \mathcal{P}_{routing}$ and nodes $A_2,\ldots,A_n \in V$; and*
- *$P_0(S,D)$ is the only process that contains an action like $out(end(l))$.*

Definition 3 states that a valid configuration is a configuration that consists of: $P_0(S,D)$, with honest source S and destination D, which is the only process that witnessing the route, and protocol roles where the related agents are located at the right place. Below we recall the attack on a routing protocol $\mathcal{P}_{routing}$.

Definition 4 (Attack on $\mathcal{P}_{routing}$ and P_0 w.r.t. $\mathcal{I}$ [CDD12]). *Let $\mathcal{P}_{routing}$ be a routing protocol, and P_0 be a routing role. Let $\mathcal{T} = (G,\mathcal{M},S,D)$ be a topology, and $\mathcal{I}$ be a set which represents the initial knowledge. We say that there is an attack on $\mathcal{P}_{routing}$ and P_0 in $\mathcal{T}$ with respect to $\mathcal{I}$ if, there exists a configuration K that is valid for $\mathcal{P}_{routing}$ and P_0 with respect to $\mathcal{T}$ and $\mathcal{I}$ such that K admits an attack in $\mathcal{T}$.*

4 Reduction Procedure

We show that if there is an attack on route validity in a given topology then there is an attack in a smaller topology obtained by doing some reduction in the initial one. Our reduction procedure consists of two main steps:

1. Adding edges to the graph yielding a quasi-complete topology.
2. Merging nodes that have the same nature (honest or malicious) and same neighbours.

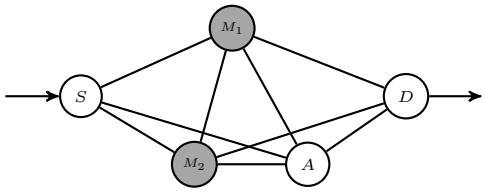
Finally in Section 4.3, we consider an arbitrary topology and apply our procedure on it. We end up with five particular topologies that contain at most three malicious nodes such that if there exists a network topology admitting an attack then there is an attack on one of these five topologies.

4.1 From an Arbitrary Topology to a Quasi-Complete One

Projecting nodes and reducing the size of the graph require that the nodes to be merged have the same nature and same neighbours. In order to ensure that most of the nodes have the same neighbours we first add edges to the graph. Actually, we add all edges except one. We show that the attack is preserved when we add these edges.

Definition 5 (Quasi-completion [CDD12]). *Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$, and A, B be two nodes in V that are not both malicious and such that $(A, B) \notin E$. The quasi-completion of $\mathcal{T}$ with respect to (A, B) is a topology $\mathcal{T}^+ = (G^+, \mathcal{M}, S, D)$ such that $G^+ = (V, E^+)$ with $E^+ = V \times V \setminus \{(A, B), (B, A)\}$.*

For example, a possible quasi-completion $\mathcal{T}_0^+$ of the topology $\mathcal{T}_0$ of Figure 2 is the one with respect to the pair (S, D) given below. As we see the graph is almost highly connected, the only missing edge is (S, D).



Definition 6 (Completion-friendly [CDD12]). *A predicate p is completion-friendly if $[\![p(t_1, \ldots, t_n)]\!]_G = true$ implies that $[\![p(t_1, \ldots, t_n)]\!]_{G^+} = true$ for any ground terms $t_1, \ldots, t_n$ and any quasi-completion $\mathcal{T}^+ = (G^+, \mathcal{M}, S, D)$ of $\mathcal{T} = (G, \mathcal{M}, S, D)$. We say that a routing protocol (resp. a configuration) is completion-friendly if the predicates $\mathbf{P_D}$, i.e. the predicates that are dependent of the graph are completion-friendly.*

Predicates have to be completion-friendly so that their values are preserved when adding some edges to the graph.

Lemma 1 (Quasi-completion). *Let $\mathcal{T}$ be a topology, K_0 be a configuration that is completion-friendly. If there is an attack on K_0 in $\mathcal{T}$, then we can find two non-neighbour nodes $B, C \in V$ that are not both malicious and a topology $\mathcal{T}^+$ quasi-completion of $\mathcal{T}$ with respect to (B, C), such that there exists an attack on K_0 in $\mathcal{T}^+$.*

Proof. We give the sketch of the proof, full proof is available in the technical report [KLL13].

Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$ and K_0 be a configuration that is completion-friendly. If there is an attack on K_0 in $\mathcal{T}$ then, by the definition of the attack, there exist A, P, $\mathcal{P}$, $\mathcal{I}$ and $l_0 = [A_1, \ldots, A_n]$, such that $K_0 \rightarrow^*_{\mathcal{T}} (\lfloor out(end(l_0)).P \rfloor_A \cup \mathcal{P}; \mathcal{I}) = K$ and l_0 is not a valid route in $\mathcal{T}$, *i.e.* there exists $1 \leq a \leq n$ such that $(A_a, A_{a+1}) \notin E$ and ($A_a \notin \mathcal{M}$ or $A_{a+1} \notin \mathcal{M}$). Consider the quasi-completion $\mathcal{T}^+ = (G^+, \mathcal{M}, S, D)$ of $\mathcal{T}$ with respect to $(B, C) = (A_a, A_{a+1})$. The edge (A_a, A_{a+1}) is missing in $\mathcal{T}^+$, thus l_0 is not a valid route in $\mathcal{T}^+$.

We show by induction on the length r of a derivation $K_0 \rightarrow^r_{\mathcal{T}} K_r$ that K_r is completion-friendly and that $K_0 \rightarrow^r_{\mathcal{T}^+} K_r$. This will allow us to obtain that $K_0 \rightarrow^*_{\mathcal{T}^+} (\lfloor out(end(l_0)).P \rfloor_A \cup \mathcal{P}; \mathcal{I})$, and thus we conclude that K_0 admits an attack in $\mathcal{T}^+$. We distinguish cases according to the rule involved in the step $K_{r-1} \rightarrow_{\mathcal{T}} K_r$. In the case of the rule IF-THEN since K_{r-1} is completion-friendly and $[\![\Phi]\!]_G = true$ then $[\![\Phi]\!]_{G^+} = true$, it follows that we can apply the rule IF-THEN on K_{r-1} in $\mathcal{T}^+$, and thus we get that $K_{r-1} \rightarrow_{\mathcal{T}^+} K_r$. For rules COMM and IN we can easily conclude since $E \subseteq E^+$, and for other rules it is straightforward as they do not depend on the underlying graph. □

4.2 Reducing the Size of the Topology

In this step, we merge nodes that have the same nature and same neighbours. The initial knowledge of malicious nodes are joined when they merged. In fact, sometimes one malicious node could do the job of several malicious nodes if we give it the required initial knowledge, for instance the case where we have a chain of malicious nodes. Also, in some cases existence or absence of some malicious nodes has no effect. We show that if there exists an attack in a given topology $\mathcal{T}$ then there exists an attack in a reduced topology $\rho(\mathcal{T})$ (some times written $\mathcal{T}\rho$) where ρ is a node renaming mapping.

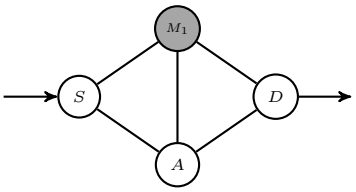
Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$, and such that E is a reflexive and symmetric relation. Similarly to [CDD12], we say that a renaming $\rho : V \mapsto V$ on agent names:

- *preserves honesty* of $\mathcal{T}$ if, $\rho(A) \in \mathcal{M}$ if and only if $A \in \mathcal{M}$ for every $A \in V$.
- *preserves neighbourhood* of $\mathcal{T}$ if, $\rho(A) = \rho(B)$ implies that A and B have the same set of neighbours.

We use $t\rho$ to denote the application of the renaming ρ on term t. We extend this notion to to set of terms, configurations, graphs, and topologies. For example we denote by $G\rho$, with $G = (V, E)$, the graph $(V\rho, E')$ where

$E' = \{(\rho(A), \rho(B))|(A, B) \in E\}$. Note that when we apply a renaming ρ to a configuration $K = (\mathcal{P}, \mathcal{I})$ then the knowledge $I_i \in \mathcal{I}$ of $M_i \in \mathcal{M}$ is joined with the knowledge $I_{i'}$ of $M_i\rho = M_{i'}$ and the I_i is removed from $\mathcal{I}$.

Consider the quasi-completion $\mathcal{T}_0^+$ we seen before, a possible renaming ρ_0 that preserves neighbourhood and honesty and that allows us to reduce the size of the graph is defined by: $\rho_0(S) = S, \rho_0(A) = A, \rho_0(M_1) = \rho_0(M_2) = M_1, \rho_0(D) = D$. The resulting topology $\mathcal{T}_0^+\rho_0$ is given as follows:



Here, the two malicious nodes M_1 and M_2 are merged in M_1 then the knowledge I_2 corresponding to M_2 should be pooled with I_1 that of M_1. For instance, assume that we have initially $I_1 = \{M_1, S, D\}$, $I_2 = \{M_2, S, A\}$ and $\mathcal{I} = \{I_1, I_2\}$ then after merging we have that $I_1\rho_0 = \{M_1, S, D, A\}$ and $\mathcal{I}\rho_0 = \{I_1\rho_0\}$.

Note that ρ_0 does not preserve neighbourhood of the topology $\mathcal{T}_0$, this emphasises the importance of the completion step in order to make a safe merging.

Definition 7 (Projection-friendly [CDD12]). *A predicate p is projection-friendly if $[\![p(t_1, \ldots, t_n)]\!]_G = true$ implies $[\![p(t_1\rho, \ldots, t_n\rho)]\!]_{G\rho} = true$ for any ground terms $t_1, \ldots, t_n$ and any renaming ρ that preserves neighbourhood and honesty. A function f over terms is projection-friendly if $f(t_1\rho, \ldots, t_n\rho)) = f(t_1, \ldots, t_n)\rho$ for any ground terms $t_1, \ldots, t_n$ and any renaming ρ that preserves neighbourhood and honesty. We say that a routing protocol (resp. a configuration) is projection-friendly if the predicates $\mathbf{P_I} \cup \mathbf{P_D}$ and the functions in $\mathcal{F}$ are projection-friendly.*

Lemma 2 (Reducing). *Let K_0 be a projection-friendly configuration, and let $\mathcal{T}$ be a topology. If there is an attack on K_0 in $\mathcal{T}$, then we can respectively obtain from K_0 and $\mathcal{T}$ a configuration K_0' and a topology $\mathcal{T}'$, using some renaming ρ that preserves neighbourhood and honesty, such that there is an attack on K_0' in $\mathcal{T}'$.*

Proof. We give the sketch of the proof, full proof is available in the technical report [KLL13].

Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$ and K_0 be a configuration that is projection-friendly. If there is an attack on K_0 in $\mathcal{T}$ then, by the definition of the attack, there exist A, P, $\mathcal{P}$, $\mathcal{I}$ and $l_0 = [A_1, \ldots, A_n]$, such that $K_0 \rightarrow_{\mathcal{T}}^* K = (\lfloor out(end(l_0)).P \rfloor_A \cup \mathcal{P}; \mathcal{I})$ and l_0 is not a valid route in $\mathcal{T}$. Let $K_0' = K_0\rho$ and $\mathcal{T}' = \mathcal{T}\rho$, we show:

1. by induction on the length r of a derivation $K_0 \rightarrow_{\mathcal{T}}^r K_r$ that K_r is projection-friendly and $K_0' \rightarrow_{\mathcal{T}'}^r K_r'$ with $K_r' = K_r\rho$. We reason on case analysis according to the rule involved in the step $K_{r-1} \rightarrow_{\mathcal{T}} K_r$. This allow us to obtain that $K_0' \rightarrow_{\mathcal{T}'}^* K'$ with $K' = K\rho$.

2. $l_0\rho = [A_1\rho, \ldots, A_n\rho]$ is not a valid route in $\mathcal{T}'$. We show that if $B \notin \mathcal{M}$ then $B\rho \notin \mathcal{M}\rho$, and if $(B_1, B_2) \notin E$ then $(B_1\rho, B_2\rho) \notin E\rho$. Thus, as there exists $1 \leq a \leq n$ such that $(A_a, A_{a+1}) \notin E$ and ($A_a \notin \mathcal{M}$ or $A_{a+1} \notin \mathcal{M}$) since l_0 is not an admissible path in $\mathcal{T}$, we deduce that $(A_a\rho, A_{a+1}\rho) \notin E\rho$ and ($A_a\rho \notin \mathcal{M}\rho$ or $A_{a+1}\rho \notin \mathcal{M}\rho$). Hence, $l_0\rho$ is not a valid route in $\mathcal{T}'$.

Therefore, we can conclude. □

4.3 Five Topologies are Sufficient

We show that for a protocol $\mathcal{P}_{routing}$ there is an attack on an arbitrary topology if and only if there is an attack on one of five particular topologies. Our result holds for an unbounded number of sessions since we consider arbitrarily many instances of the roles occurring in $\mathcal{P}_{routing}$. Note that, Theorem 1 extends the result of [CDD12] to the case where malicious nodes don't share their knowledge.

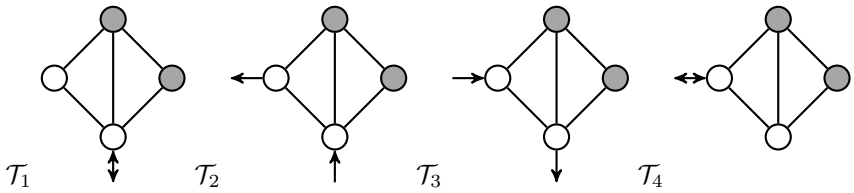
Theorem 1 (Five topologies). *Let $\mathcal{I}$ be a set of knowledge, and let $\mathcal{P}_{routing}$ be a routing protocol and P_0 be a routing role which are completion-friendly and projection-friendly. There exists a topology $\mathcal{T}$ such that there is an attack on $\mathcal{P}_{routing}$ and P_0 in $\mathcal{T}$ with respect to $\mathcal{I}$, if and only if, there are five particular topologies: $\mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3$, $\mathcal{T}_4$ and $\mathcal{T}_5$, such that there is an attack on $\mathcal{P}_{routing}$ and P_0 with respect to $\mathcal{I}$ in one of them.*

Proof. If there is an attack on $\mathcal{P}_{routing}$ and P_0 with respect to $\mathcal{I}$ in one of the five particular topologies, we easily conclude that, there exists a topology $\mathcal{T}$ such that there is an attack on $\mathcal{P}_{routing}$ and P_0 in $\mathcal{T}$ with respect to $\mathcal{I}$. We consider now the other implication. Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$, $\mathcal{I}$ be a set of knowledge and $K = (\mathcal{P}, \mathcal{I})$ be a valid configuration for $\mathcal{P}_{routing}$ and P_0 with respect to $\mathcal{T}$, such that there is an attack on K in $\mathcal{T}$. Without lost of generality, we assume that V contains at least three distinct honest nodes and three distinct malicious nodes. Note that otherwise, it is easy to add some nodes in the topology $\mathcal{T}$ and still preserving the existence of an attack.

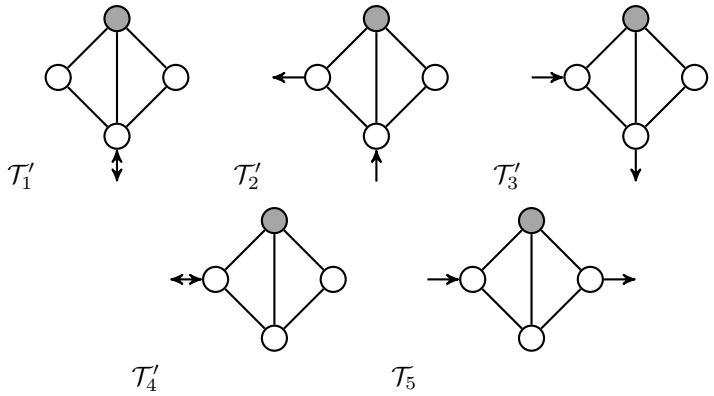
First, it is easy to see that K is completion-friendly as $\mathcal{P}_{routing}$ and P_0 are both completion-friendly. Thanks to the Lemma 1, we deduce that there exists two non-neighbour nodes $B, C \in V$ that are not both malicious and a topology $\mathcal{T}^+ = (G, \mathcal{M}, S, D)$, a quasi-completion of $\mathcal{T}$ with respect to (B, C), such that there is an attack on K in $\mathcal{T}^+$. As $\mathcal{T}^+$ is a quasi-completion of $\mathcal{T}$ with respect to a pair (B, C), then the neighbours of B in G^+ denoted $N_{G^+}(B) = V \setminus \{C\}$, $N_{G^+}(C) = V \setminus \{B\}$, and $N_{G^+}(W) = V$ for any $W \in V \setminus \{B, C\}$. Since we have assumed that V contains at least three distinct nodes that are not in $\mathcal{M}$ and three distinct nodes in $\mathcal{M}$, we deduce that $V \setminus \{B, C\}$ contains at least an honest node let us say A and a malicious one let us say M. Let ρ be a renaming on the agent names such that for any $W \in V \setminus \{B, C\}$, $\rho(W) = A$ if $W \notin \mathcal{M}$ and $\rho(W) = M$ else. Clearly, we have that ρ preserves honesty and neighbourhood. Thanks to Lemma 2, we deduce that there is an attack on $K' = K\rho$ in $\mathcal{T}' = (G\rho, \mathcal{M}\rho, S\rho, D\rho) = \mathcal{T}^+\rho$.

The topology $\mathcal{T}'$ has four nodes: one honest, one malicious and two nodes B, C. We distinguish cases depending in the nature of the nodes B and C:

1. B honest and C malicious (the reverse is the same due to symmetry). In this case $\mathcal{T}'$ has two honest nodes, thus according to the position of the source and destination we have the following four possibilities:



   Note that the topology $\mathcal{T}_4$ can obtained only if the source and destination are the same in the original topology.
2. Both are honest. So $\mathcal{T}'$ has three honest nodes in this case. Depending on the position of the source and destination we have nine possibilities, but due to symmetry four of them can be eliminated. This results in only five topologies:



   Again the topologies $\mathcal{T}_1', \mathcal{T}_2', \mathcal{T}_3'$ and $\mathcal{T}_4'$ are subsumed by $\mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3$ and $\mathcal{T}_4$ respectively, since if there is an attack in $\mathcal{T}_i'$ for $i \in \{1, 2, 3, 4\}$, then this attack can be mounted in $\mathcal{T}_i$ where an honest node is now malicious.

So $\mathcal{T}'$ is one of the five topologies $\mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4$ and $\mathcal{T}_5$. Now, since $\mathcal{P}_{routing}$ and P_0 do not contain any names, Definition 3 is satisfied and thus $K' = (\mathcal{P}\rho, \mathcal{I}\rho)$ is a valid configuration with respect to $\mathcal{T}'$. □

5 Comparison Between the Two Models

We show the equivalence of cooperative model and non-cooperative one when considering all possible topologies. First, if we have a topology $\mathcal{T}$ that a protocol admits an attack under the cooperative model, we show how to obtain a topology $\mathcal{T}'$ from such $\mathcal{T}$ that this protocol admits an attack on it under the non-cooperative model. Then, we present the equivalence theorem.

Lemma 3 (Preservation of the attack). *Let K be a configuration that is completion friendly. If there exists a topology $\mathcal{T}$ such that the configuration K*

admits an attack in $\mathcal{T}$ under the cooperative model then there exists a topology $\mathcal{T}'$ to be obtained from $\mathcal{T}$ such that K admits an attack in $\mathcal{T}'$ under the non-cooperative model.

Proof. Let $\mathcal{T} = (G, \mathcal{M}, S, D)$ be a topology with $G = (V, E)$ and K be a configuration that is completion friendly. Suppose that there is an attack on K in $\mathcal{T}$ then, by the definition of the attack, there exist A, P, $\mathcal{P}$, $\mathcal{I}$ and $l_0 = [A_1, \ldots, A_n]$ such that $K \rightarrow^*_{\mathcal{T}} (\lfloor out(end(l_0)).P \rfloor_A \cup \mathcal{P}; \mathcal{I})$ and l_0 is not a valid route in $\mathcal{T}$.

Let $\mathcal{T}' = (G', \mathcal{M}, S, D)$ be a topology such that $G' = (V \cup \{M_0\}, E')$ with $E' = E \cup (\mathcal{M} \cup \{M_0\} \times \mathcal{M} \cup \{M_0\})$, and $M_0 \in \mathcal{M}$ **is a special malicious node that is ready to input an infinite number of messages of any form,** *i.e.* $\lfloor P \rfloor_{M_0} = \lfloor P' | !in(w) \rfloor_{M_0}$ **with** $w \in \mathbb{X} \setminus (vars(K) \cup vars(P'))$. Since l_0 is inadmissible in $\mathcal{T}$, it is also inadmissible in $\mathcal{T}'$ according to the definition. To deduce that there is an attack on K in $\mathcal{T}'$ we show that $K \rightarrow^*_{\mathcal{T}'} (\lfloor out(end(l_0)).P \rfloor_A \cup \mathcal{P}; \mathcal{I})$. First, in order to homogenize the initial knowledge of the attackers, the IN rule has to be applied by each malicious node M_i toward node M_0 a certain number of times (equal to the cardinality of its initial knowledge I_i) to transmit its knowledge to other malicious nodes. This is possible since M_0 is ready to input any number of (any) messages. When a node M_i sent a message m to M_0 all malicious nodes will get m too since they are all connected in $\mathcal{T}'$. Then, for each rule involved in the transition $K_r \rightarrow_{\mathcal{T}} K_{r+1}$ under the cooperative model we show the equivalence rule or rules in $\mathcal{T}'$ under non-cooperative model to have $K_r \rightarrow^*_{\mathcal{T}'} K_{r+1}$

- **Case of the rule IF-THEN:** Since K is completion friendly then any formula ϕ that is true for $\mathcal{T}$, its true also for $\mathcal{T}'$. Thus, the rule IF-THEN can also be applied in $\mathcal{T}'$ in this case.
- **Case of the rule IN:** Since $E \subseteq E'$ the same rule can be applied and as all malicious nodes are connected in $\mathcal{T}'$ the sent message is received by all attackers so the knowledge remains equal.
- **Case of the COMM:** Since $E \subseteq E'$ we can apply the rule COMM. However, in case where we have a malicious node M_i that is a neighbour of the sender of the message, then the rule COMM should be followed by an application of rule IN from M_i toward M_0. So that, all other malicious nodes will get that message. This last step is for a malicious node that has received a message to share it in an indirect way with all the other malicious nodes.
- **Case of the rules PAR, REPL, and NEW:** These rules do not depend on the underlying graph. So same rules can be applied in $\mathcal{T}'$. □

Theorem 2 (Equivalence). *Let $\mathcal{P}_{routing}$ be a routing protocol and P_0 be a routing role and $\mathcal{I}$ be a set of knowledge. We have that $\mathcal{P}_{routing}$ and P_0 given the knowledge $\mathcal{I}$ are secure for any $\mathcal{T}$ in the cooperative model, if and only if, $\mathcal{P}_{routing}$ and P_0 given the knowledge $\mathcal{I}$ are secure for any $\mathcal{T}$ in the non-cooperative model.*

Proof. First direction: in non-cooperative model the malicious nodes have weaker abilities. So, if there is no attack on $\mathcal{P}_{routing}$ and P_0 given $\mathcal{I}$ in cooperative model then there is no attack on $\mathcal{P}_{routing}$ and P_0 in the non-cooperative model.

Second direction: Suppose that there is no attack on $\mathcal{P}_{routing}$ and P_0 given $\mathcal{I}$ for any topology in the non-cooperative model. Assume that there exists a

topology $\mathcal{T}$ such that there is an attack on $\mathcal{P}_{routing}$ and P_0 given $\mathcal{I}$ in $\mathcal{T}$ for cooperative model, then by the definition of the attack there are a configuration K that is valid for $\mathcal{P}_{routing}$ and P_0 such that there is an attack on K in $\mathcal{T}$ under cooperative model. Then, by Lemma 3, there is a topology $\mathcal{T}'$ obtained from $\mathcal{T}$ such that there is an attack in it on the configuration K for the non-cooperative model and thus an attack on $\mathcal{P}_{routing}$ and P_0 given $\mathcal{I}$ in $\mathcal{T}'$ which leads to a contradiction. □

Considering one fix topology $\mathcal{T}$ this equivalence do not hold anymore as we can find an attack on a protocol in $\mathcal{T}$ under the cooperative model, while this protocol is secure in $\mathcal{T}$ under the non-cooperative model. This due to the fact that under the cooperative model we give the malicious nodes a powerful capabilities that are not exists in reality, this leads to a false positive attacks that can not be mounted in practice. Having a fixed known topology one could prefer to verify the used protocol under the non-cooperative model which gives a more realistic security level.

6 Conclusion

We consider the non-cooperative attacker model where there are multiple attackers working independently, so that no one share any of its knowledge with the others. We give a reduction proof: when looking for attacks on route validity in presence of multiple independent attackers if there is an attack in a certain topology then there is an attack in a smaller one. Then, we show that there is an attack on an arbitrary topology if and only if there is an attack on one of five particular topologies, each of them having only four nodes. This result facilities verification of routing protocols as we have to check only five small topologies. Finally, we show that a protocol is secure in any topology under the cooperative model if and only if it is secure for any topology under the non-cooperative model.

For future work, it could be interesting to develop a tool that able to solve multiple attackers constraints, so that we can reason on the five topologies one by one in order to verify ad-hoc network routing protocols.

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