Key Revocation Based on Dirichlet Multinomial Model for Mobile Ad Hoc Networks

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***Abstract*— The absence of an online trusted authority makes the issue of key revocation in mobile ad hoc networks (MANETs) particularly challenging. In this paper, we present a novel self-organized key revocation scheme based on the Dirichlet multinomial model and identity-based cryptography (IBC). Our key revocation scheme offers a theoretically sound basis for a node in MANETs to predict the behavior of other nodes based on its own observations and reports from peers. In our scheme, each node keeps track of three categories of behavior defined and classified by an external trusted authority, and updates its knowledge about other nodes' behavior with 3-dimension Dirichlet distribution. Differentiating between suspicious behavior and malicious behavior enables nodes to make multilevel response by either revoking keys of malicious nodes or ceasing the communication with suspicious nodes for some time to gather more information for making further decision. Furthermore, we also analyze the attack-resistant properties of our key revocation scheme through extensive simulations in the presence of independent and collusive adversaries, respectively.**

***Index Terms*— Mobile ad hoc networks, security, key revocation, identity-based cryptography, Dirichlet multinomial model.**

I. Introduction

With the rapid development in network technology, in particular wireless communication, the traditional centralized, fixed networks cannot satisfy enormous demands on network connectivity, data storage and information exchange any longer. New types of communication networks based on wireless and multi-hop communication have emerged to provide efficient solutions for the growing number of mobile wireless applications and services. A large family of the new types of wireless communication networks can be best represented by *mobile ad hoc networks (MANETs)*. MANETs provide a relative new paradigm of wireless networking, in which all networking functions (e.g., control, routing, monitoring, mobility management, etc.) are performed by the nodes themselves in a decentralized manner. Security support is indispensable in order for these networks and related services to be implemented in both military and commercial applications. However, due to the absence of infrastructure, insecure nature of the wireless communication medium and dynamic changes of the network topology, MANETs are vulnerable to a range of attacks and are thus difficult to secure [1], [5]. In this paper, we address the key revocation, one of the most important and challenging issues for the key management in MANETs. Although a number of schemes have been proposed for the key management in MANETs [9], [18], [24], [28]–[30], only a few of literature explicitly address the issue of the key revocation, see [2], [12], [18], [21], [24], [29] for example.

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Revoking cryptographic keys or certificates of malicious nodes is crucial for the security and robustness of MANETs. Namely, good nodes can isolate malicious ones from the network by ceasing the further communication with them and ignoring any message received from them. Therefore, if cryptographic keys or certificates are issued by an authority, it must possible, whenever necessary (e.g., key compromise), for the authority to revoke them, and essentially evict malicious nodes from the network. In the context of wired networks, implementations of key revocation schemes are usually based on Public Key Infrastructures (PKIs). When the certificate of some user is to be revoked, the certificate authority (CA) adds user's certificate information into a Certificate Revocation List (CRL) and puts it on an on-line trusted public repository or distributes it to other relevant users in some secure way. However, these conventional techniques are difficult to be applied to MANETs because of a number of unique features of MANETs such as the absence of an on-line CA and a centralized repository. Two categories of solutions have been proposed for the key revocation in MANETs and each of them can be implemented with the certificate-based cryptography (CBC) or identity-based cryptography (IBC). In the first category of solutions, a trusted third party (TTP) distributes the trust over some or all network nodes using threshold cryptography, thereby letting these nodes take over the responsibility of key revocation in MANETs. Although this kind of key revocation schemes do not require the establishment of any infrastructure, the use of threshold cryptography may cause tremendous computation and communication overhead on the network. Meanwhile, the second category of solutions are fully self-organized, in which a TTP loads public key certificates (in CBC schemes) or private keys (in IBC schemes) for nodes before they join the network. Each node has its own view about the network and decides whether certificates or private keys of other nodes should be revoked based on its own observations and the information collected from peers in MANETs. Our key revocation scheme proposed in this paper belongs to this category.

We note that the key revocation procedure involves observations and interactions among nodes. Therefore, it is closely related to reputation and trust of nodes in the network. This observation allows us to design a key revocation scheme based on the decentralized reputation system. Reputation systems have been investigated extensively in the past and used successfully in many commercial online applications

[17]. They provide a mechanism for rating participants of transactions by having buyers and sellers compute each other reputation scores, and therefore stimulate good behavior as well as sanction bad behavior. In the context of MANETs, reputation systems have emerged as a promising mechanism for ensuring cooperation and fairness, and thwarting node failures and malicious attacks [6], [8], [19]. However, the previous reputation systems all classify the behavior of nodes in MANETs as either *good* or *bad* without any intermediate state. Such a binary behavior differentiation omits the actual cause and the degree of the misbehavior. Note that some misbehavior may just happen accidently (for example, a node cannot forward packages due to temporary congestion of the network) and last only for a short time. When a node shows this kind of accidental misbehavior, it might not mean that the node has been compromised by an attacker. Therefore, in this case it is more reasonable to keep collecting information about the behavior of this node instead of immediately characterizing it as malicious and excluding it from the network.

To provide more flexibility and precision for nodes analyzing peers' behavior and making different response based on results of the analysis, we present a novel self-organized key revocation scheme based on IBC and Dirichlet multinomial model in this contribution. In our scheme, depending on different application scenarios, an external TTP classifies nodes' behavior into three categories during the network initialization phase, namely good behavior, suspicious behavior, and malicious behavior. Each node keeps track of peers' behavior with a neighborhood watch scheme or by analyzing other nodes' reports, and then updates its own knowledge about peers' behavior with 3-dimensional Dirichlet distribution and makes the corresponding response. Furthermore, a deviation test is employed to filter potentially false statements from adversaries and Dampster-Shafer belief theory [25] is used to integrate other nodes' reports. While a node revokes the keys of nodes showing malicious behavior once enough evidence has been collected, it also shields itself from suspicious behavior of peers by ceasing the communication with them and continue gathering information for further decisions.

The rest of this paper is organized as follows: Section II reviews existing solutions and describes the motivation for our work. Section III gives a short introduction to mathematical tools used in this paper including cryptographic pairings and Dirichlet multinomial model. Section IV formulates the network and security models and presents our design goals. Section V gives a detailed description of our key revocation scheme, followed by simulations and analysis of our key revocation scheme under false statement attacks by independent and collusive adversaries in Section VI. This paper is finally concluded in Section VII.

II. Related Work and Motivation

In this section, we briefly review previous work about the key revocation and reputation systems in MANETs, restricting our attention to the schemes which are more relevant to our work. We also describe the motivation that leads to the design of our protocol at the end. In the following discussions, N denotes the overall number of network nodes, and t and n are two positive integers satisfying $t \leq n < N$.

A. Key Revocation Schemes in MENETs

The seminal paper by Zhou and Hass [30] introduced the idea of using (t, n)-threshold cryptography to implement distributed CAs (D-CAs) in MANETs. Although the authors mentioned that the D-CAs can collaborate to revoke certificates of malicious nodes, no algorithms about the certificate revocation are described.

Luo *et al.* [18] presented a certificate revocation scheme based on CBC and (t, N)-threshold cryptography. In their scheme, each node monitors the behavior of its one-hop neighboring nodes and disseminates its signed accusations to its m-hop neighborhoods upon observing any malicious behavior, where m is a design parameter denoting the range of the accusation propagation. All nodes receiving the accusation information verify whether the accuser can be trusted and update their CRLs accordingly. When the number of accusations for some node exceeds a predefined revocation threshold, the certificate of that node will be revoked. Similar idea is also implemented with IBC in [24].

Zhang *et al.* [29] designed a novel key management mechanism called IKM for MANETs by combining IBC and threshold cryptography. In their key revocation protocol, each node observing misbehavior of other nodes securely sends its signed accusations to preassigned Distributed Private Key Generators (D-PKGs). When the number of accusations reaches the revocation threshold in a predetermined time window, t D-PKGs collaborate to revoke keys of malicious nodes based on an ID-based (t, n)-threshold signature scheme.

The above schemes use threshold cryptography and therefore some nodes need to collaborate to revoke keys of malicious nodes, whereas several fully self-organized scheme are also proposed in the literature. Moore *et al.* [21] introduced the concept of suicide for solving the credential revocation in self-organizing systems. The basic idea is extremely simple: when a node observes the misbehavior of another node, it simply broadcasts a signed message claiming both of them to be dead. Their scheme can fast isolate the malicious nodes from the network and is ideally suited to highly mobile networks or special-purpose MANETs.

Arboit *et al.* [2] proposed a self-organized certificate revocation protocol that is based on a weighted accusation scheme and provides protection against potentially false accusation attacks. The authors presented a method for actually quantifying the trustworthiness of nodes in MANETs satisfying that accusations from trustworthy nodes have higher weight than those from less trustworthy nodes. All accusations are frequently broadcasted throughout the entire network. The certificate of a node is revoked when the sum of the weighted accusations against that node is equal to or greater than a configurable threshold.

Hoeper and Gong [12] presented a self-organized key revocation scheme for MANETs. In their scheme, each node uses a neighborhood watch scheme to monitor other nodes' behavior within its communication range. Upon detection of

misbehavior, these observations are then securely propagated to m-hop neighborhoods using preshared keys obtained from a non-interactive ID-based key agreement protocol. The public key of a node will be revoked if it is accused by at least δ nodes, where δ is a revocation threshold. Moreover, the authors also use the majority vote to mitigate the influence of false accusations from l-hop neighbors, where $2 \leq l \leq m$.

B. Reputation Systems in MANETs

Several reputation systems have been proposed in the literature to cope with malicious behavior of nodes in MANETs [6], [8], [19]. Much closer to our work is the reputation system CONFIDANT (Cooperation Of Nodes, Fairness In Dynamic Ad-hoc NeTworks) proposed by Buchegger and Boudec [6], [8]. CONFIDANT adopts the classical Bayesian inference theory and beta-binomial framework for estimating reputations [10], [14]. Moreover, CONFIDANT includes a deviation test based on the Bayesian approach to decide whether second-hand information that a node received from its one-hop neighbors can be trusted, and to mitigate the influence of potentially false accusation attacks from malicious nodes.

C. Motivation

As we have mentioned in Section 1, it might be more reasonable and more precise to analyze and predict nodes' behavior by differentiating multi-categories of misbehavior based on their actual cause. In this way, we hope that keys of good nodes who only misbehave for a short time due to various reasons will not be immediately revoked by other good nodes. However, the more categories of malicious behavior, the more complicated the implementation. Thus, in this paper we only consider two categories of misbehavior, namely suspicious behavior and malicious behavior. To establish multi-parameter Bayesian model for analyzing nodes' behavior, we employ Dirichlet reputation systems (DRSs) proposed by Jøsang and Haller [16] and make some modifications about the information integration based on Dampster-Shafer belief theory. As a generalization of Beta reputation systems [14], DRSs can define any set of discrete rating levels and provide great flexibility and usability.

III. Preliminaries

In this section, we present a brief introduction to IBC, bilinear pairing, and Dirichlet multinomial model, which form the basis of our design in this work. For a detailed treatment, the reader is referred to references mentioned below.

A. IBC and Bilinear Pairing

The concept of IBC is due to Shamir [26]. In an ID-based cryptosystem, a user's public key is an easily calculated function of his identity, while his private key can be computed by a TTP. Recently, IBC has been used to design efficient key management protocols for MANETs [11], [29]. All these protocols use so-called bilinear pairings. Due to the important role of bilinear pairings in IBC, we give a brief introduction about the concept of bilinear pairings below.

Let r be a positive integer. Let $\mathbb{G}_1$ and $\mathbb{G}_2$ be additively-written abelian groups of order r with identity $\mathcal{O}$, and let $\mathbb{G}_T$ be a multiplicatively-written cyclic group of order r with identity 1. A *bilinear pairing* on $(\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T)$ is a map

$$e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_T$$

that satisfies the following additional properties:

1) **Bilinearity:** For $\forall P, P' \in \mathbb{G}_1$ and $\forall Q, Q' \in \mathbb{G}_2$ we have $e(P + P', Q) = e(P, Q)e(P', Q)$ and $e(P, Q + Q') = e(P, Q)e(P, Q')$.
2) **Non-degeneracy:** For $\forall P \in \mathbb{G}_1$ with $P \neq \mathcal{O}$, there is some $Q \in \mathbb{G}_2$ such that $e(P, Q) \neq 1$. Furthermore, for $\forall Q \in \mathbb{G}_2$ with $Q \neq \mathcal{O}$, there is some $P \in \mathbb{G}_1$ such that $e(P, Q) \neq 1$.
3) **Computability:** $e(P, Q)$ can be efficiently computed for all $P \in \mathbb{G}_1$ and $Q \in \mathbb{G}_2$.

In practice, the abelian groups $\mathbb{G}_1$ and $\mathbb{G}_2$ are implemented using a divisor class group on certain (hyper-)elliptic curves and the cyclic group $\mathbb{G}_T$ is implemented using a multiplicative subgroup of a finite field. Most pairing applications rely on the hardness of the so-called *Bilinear Diffie-Hellman Problem* (BDHP)[1]. For more details, the reader is referred to [3].

B. Dirichlet Multinomial Model

Dirichlet multinomila model [10] provides a flexible mechanism for constructing reputation system for e-commerce applications. The basic idea behind DRS [16] is to compute reputation values by statically updating Dirichlet probability density function (PDF). Given the *a priori* reputation values, the *a posteriori* reputation value is calculated to increase the precision of a belief by combining the *a priori* knowledge and the new observations.

It is well known that the Dirichlet distribution, often denoted by $\mathsf{Dir}(\vec{\alpha})$, is a family of continuous multivariate probability distributions parameterized by the vector $\vec{\alpha}$ of positive reals which captures a sequence of observations of the possible outcomes in a state space. The Dirichlet distribution is defined as follows: Let $\Theta = \{\theta_1, \ldots, \theta_k\}$ be a state space consisting of k mutually disjoint events. Let $\vec{p} = (p(\theta_1), \ldots, p(\theta_k))$ be a continuous random vector taking values in the k-dimension simplex[4] with the joint PDF

$$f(\vec{p} \mid \vec{\alpha}) = \frac{\Gamma\left(\sum_{i=1}^{k} \alpha(\theta_i)\right)}{\prod_{i=1}^{k} \Gamma\left(\alpha(\theta_i)\right)} \prod_{i=1}^{k} p(\theta_i)^{\alpha(\theta_i)-1},$$

where $\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt$ is the Gamma function. Then $\vec{p}$ is said to have a k-dimension Dirichlet distribution with parameter vector $\vec{\alpha} = (\alpha(\theta_1), \ldots, \alpha(\theta_k))$ ($\alpha(\theta_i) \geq 0$ for $i = 1, \ldots, k$). The Dirichlet distribution is the multivariate generalization of the Beta distribution and the vector of expectations is a function of the parameters $\alpha(\theta_i)$. We have

$$\mathbb{E}(p(\theta_i) \mid \vec{\alpha}) = \frac{\alpha(\theta_i)}{\sum_{i=1}^{k} \alpha(\theta_i)}.$$

[1] Let e be a bilinear pairing on $(\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T)$. The *Bilinear Diffie-Hellman Problem* (BDHP) is the following: given $P, P_1 = [a]P, P_2 = [b]P \in \mathbb{G}_1, Q \in \mathbb{G}_2$ such that $e(p, Q) \neq 1$, compute $e([ab]P, Q)$.

[4] The k-dimension simplex is such that if $\vec{p} = (p(\theta_1), \ldots, p(\theta_k))$ then $p(\theta_i) \geq 0$ and $\sum_{i=1}^{k} p(\theta_i) = 1$.

Since the Dirichlet distribution is a conjugate priori of the multinomial distribution, the posteriori distribution is also Dirichlet and can be calculated as follows [16]:

$$f(\vec{p} \mid \vec{r}, \vec{a}) = \frac{\Gamma\left(\sum_{i=1}^{k} r(\theta_i) + Ca(\theta_i)\right)}{\prod_{i=1}^{k} \Gamma\left(r(\theta_i) + Ca(\theta_i)\right)} \prod_{i=1}^{k} p(\theta_i)^{\left(r(\theta_i)+Ca(\theta_i)-1\right)}, \quad (1)$$

where $a(\theta_i)$ is a *base rate* vector over the state space Θ satisfying $a(\theta_i) \geq 0$ and $\sum_{i=1}^{k} a(\theta_i) = 1$, C is a *priori* constant which is equal to the cardinality of the state space over which a uniform distribution is assumed (C is usually set to 2), and the vector $r(\theta_i)$ is a *posteriori* evidence over the state space Θ. Given the Dirichlet distribution of Eq.(1), the probability expectation of any of the k varaiables can now be written as:

$$\mathbb{E}(p(\theta_i) \mid \vec{r}, \vec{a}) = \frac{r(\theta_i) + Ca(\theta_i)}{C + \sum_{i=1}^{k} r(\theta_i)}.$$

For more details about Dirichlet reputation systems, the reader is referred to [10], [16].

IV. System Models and Design Goals

In this section, we formulate the network model and the security model as well as design assumptions and goals.

A. Network Model

We consider a general MANET consisting of an unconstrained number of networking nodes with a random mobility pattern, i.e., nodes moving independently within a given field or keeping stationary in a location for a period of time. In addition, the network topology also changes dynamically when a particular network event, such as node join, leave or failure, occurs. Each node has limited transmission and reception capabilities. Mobile nodes that are within each other's radio range communicate directly via bandwidth-constrained, error-prone insecure wireless links, while those that are far apart rely on other nodes to relay their messages in a multi-hop fashion. As requirements of many network tasks and protocols, each node must be unambiguously identified by a unique identity. It can be a MAC address or an IP address.

In order for nodes monitoring various behavior of their direct neighbors within the communication range, we assume that communication links are bidirectional in the network and nodes are in promiscuous mode. Both assumptions are common in many low-layer MANETs protocols such as DSR [15] and AODV [23] routing protocols. Furthermore, for disseminating accusation messages securely with IBC in our key revocation scheme, we assume that nodes know identities of their neighbors up to m-hop (m is a design parameter denoting the range of the accusation propagation). Identifiers of neighbor nodes can be obtained by running some neighborhood discovery protocols, which are part of many existing routing protocols and therefore can be reused. Moreover, we also assume that embedded processors of mobile nodes can perform public-key algorithms related to IBC. We would like to point out that all the above assumptions are quite common and reasonable for most application scenarios of MANETs. Hence, our design does not introduce additional burdens into the network.

B. Security Model

We term as an *adversary* or *attacker* any node whose behavior deviates from the legitimate MANET protocols. We assume that each node in MANET is installed an Intrusion Detection System [20] which can detect predefined misbehavior of nodes. The main purpose of a key revocation scheme is to revoke keys of malicious nodes and finally isolates them from the network. Most previous schemes [18], [24], [29] are vulnerable to potentially false statement attacks in which malicious nodes accuse other nodes in a MANET at their own will. Therefore, we need to evaluate the influence of false statement attacks mounted by malicious nodes on our key revocation scheme in details. The analysis of other types of attacks aimed at the different layers of MANETs, though important, is out of the scope of this work.

The false accusation attack can be independently or collaboratively initiated by some adversaries. We consider the following two attack scenarios in this paper:

1) **Attack by independent adversaries**: in this attack scenario, each adversary independently chooses attack targets and propagates false accusations against victims through the network in order to accelerate keys of target nodes to be revoked by other nodes in the MANET. Note that in this case it is possible that an adversary also accuse other adversaries, except for accusing well-behaving nodes.
2) **Attack by collusive adversaries**: in this attack scenario, collusive adversaries know each other and they choose one or several well-behaving nodes as common attack objects. These adversaries always report positive observations about their friends and negative ones about the chosen victims. In this way, the adversaries can not only prolong their lifetime in the MANET, but also speed up the procedure of revoking keys of the victims.

Furthermore, we also assume that adversaries always attempt to maximize their influence by propagating extremely positive or extremely negative observations to the network. Detailed simulations and analysis of our scheme against the above two types of attacks are presented in Section VI.

C. Design Goals

From our point of view, an ideal key revocation scheme for MANETs should have the following properties:

1) It should be fully self-organized.
2) It should be flexible enough to deal with the information that nodes collect through their own observations and interactions with peers, and to make corresponding responses based on results of the analysis.
3) It should be able to efficiently revoke keys of malicious nodes when they show the behavior that the network cannot tolerate.
4) It should be robust enough to thwart false statement attacks mounted by independent adversaries or a number of collusive adversaries.
5) It should be efficient in terms of communication, computation and storage overhead.

V. Protocol Description

In this section, we describe our key revocation scheme in detail. We first provide an overview of our key revocation scheme in Section V-A. And then we present the detailed procedure of our protocol in Sections V-B to V-F.

A. Overview

Our fully self-organized key revocation scheme is within the framework of Bayesian data analysis. We employ Dirichlet multinomial model and explicitly use probability to quantify the uncertainty about nodes' behavior. Each node in a MANET gradually updates its knowledge about peers' behavior through interactions among them, and finally makes multilevel response based on the analysis of collected information. Furthermore, IBC is used to secure the information transmission during interactions of nodes. Our scheme consists of five parts: network initialization, neighborhood watch, authenticated information dissemination, filter of false statements, and multilevel response for malicious nodes.

In the network initialization, an external TTP first generates a set of secure system parameters for IBC. And then the TTP completes the registration of nodes by preloading each node with appropriate key materials according to the expire date and the version number of every key. Moreover, nodes' behavior is classified by the TTP into three categories: good behavior set, suspicious behavior set and malicious behavior set.

To protect the MANET from adversaries, each node overhears the wireless channel in the promiscuous mode, and monitors various behavior of its one-hop neighbors at all time with the neighborhood watch scheme. Each node records its observation and updates the knowledge about the behavior of all its one-hop neighbors. In addition, since nodes may change their behavior over time, a discount factor is introduced for the case that nodes can forget past observations gradually.

Each node not only uses direct observations to update its knowledge about one-hop neighbors' behavior, but also distributes these information to all its m-hop neighbors in some secure way. The data integrity and the authenticity of the message origin are implemented with a keyed-hash function where the key is derived from the bilinear pairing in a non-interactive fashion.

After one node receives an observation report from the other node, it first decides whether the sender can be trusted by checking the sender's key status. And then the receiver verifies the authenticity of the report with the pre-shared key between two nodes. Although merging other nodes' observations can accelerate the estimation about some subject's behavior, using all the receiving reports without hesitation will result in potentially false statement attacks from adversaries. Hence, we set two defence lines to thwart these attacks. Firstly, a deviation test based on the statistical pattern of reports is used to filter out false statements to some extent. Furthermore, if the sender's report passes the deviation test of the receiver, we will use Dempster-Shafer belief theory [25] to update the receiver's current knowledge about the behavior of the subject in question with this report.

In our key revocation model, each node considers that their peers show good behavior, suspicious behavior and malicious behavior with different probabilities. For approximating to these unknown parameters, a node uses 3-dimension Dirichlet distribution as the prior distribution of the unknown parameters, updates this distribution by either node's direct observations or its counterparts' reports, then estimates two parameters with posteriori expected probabilities and compares these values to predefined thresholds, and finally makes multilevel response based on results of comparisons. A high level description of our key revocation scheme is shown in the following Algorithm 1.

Algorithm 1 Self-Organized Key Revocation for MANETs

Step 1. Network Initialization
- ▷ Generation of system parameters
- ▷ Registration of network nodes
- ▷ Classification of node behavior

Step 2. Neighborhood Watch
- ▷ Monitor neighbors' behavior and generate observation matrix
- ▷ Update key status of nodes with direct observations

Step 3. Authenticated Information Dissemination
- ▷ Disseminate nodes' direct observations to all m-hop neighbors in an authenticated way by using a keyed-hash function

Step 4. Filter of False Statements
- ▷ Filter out potentially false statements statistically
- ▷ Update key status of nodes based on Dempster-Shafer theory

Step 5. Multilevel Response for Malicious Nodes
- ▷ Revoke keys of nodes showing malicious behavior
- ▷ Cease communication with nodes showing suspicious behavior and keep observing their behavior for further decision

B. Step 1. Network Initialization

Our scheme assumes that an external TTP bootstraps the MANET with IBC and classifies the behavior of nodes. More specifically, the external TTP will complete the following tasks during network initialization:

1) Generation of system parameters: The TTP generates secure system parameters $\langle q, k, C/\mathbb{F}_q, \mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, e\rangle$ as described in Section III-A. Note that we take $\mathbb{G}_1 = \mathbb{G}_2$ in this paper. The TTP also generates a random master key $s \in \mathbb{Z}_n^*$ and a random generator $P \in \mathbb{G}_1$, and sets his public key $P_{pub} = sP \in \mathbb{G}_1$. Finally, the TTP chooses a cryptographic secure hash function: $H : \{0,1\}^* \rightarrow \mathbb{G}_1$. The TTP publishes all of these parameters except his master key.

2) Registration of network nodes: For the purpose of key revocation, we use the public key format $Q_i = H(ID_i \parallel \mathsf{date} \parallel \mathsf{version})$ for each node with identity ID_i as introduced in [12], where date is the expiry date of the key and version is its version number. After the user ID_i shows his credential and passes the authentication of the TTP, the TTP will derive his public key Q_i and generate the corresponding ID-based private key $d_i = sQ_i$.

3) Classification of node behavior: In our model, the state space Θ includes three mutually disjoint events: good behavior θ_g, suspicious behavior θ_s and malicious behavior θ_m, namely $\Theta = \{\theta_g, \theta_s, \theta_m\}$. To keep track of various observable behavior in the lifetime of the MANET, the TTP classifies nodes' behavior into three categories, namely good behavior set $\mathbb{B}_g$, suspicious behavior set $\mathbb{B}_s$ and malicious behavior set $\mathbb{B}_m$. The set $\mathbb{B}_g$ includes behavior complying

with descriptions of the MANET protocols such as finding a path for a packet and relaying packets for others. The set $\mathbb{B}_s$ contains accidental misbehavior that temporarily and slightly deteriorate the performance of MANETs, for example node failures due to the network congestion or a lack of resources, whereas intentional misbehavior, which seriously degrade the performance of MANETs, are comprised in the set $\mathbb{B}_m$. The practical classification of the sets $\mathbb{B}_g, \mathbb{B}_s$ and $\mathbb{B}_m$ depends on the network policy, the detection ability of nodes and the concrete application scenarios.

We note that all previous key revocation schemes for MANETs [2], [12], [18], [21], [24], [29] only classify nodes' behavior as either good or malicious. The main motivation that we consider suspicious behavior is based on the observation that nodes show some misbehavior for a short time just by accident. For example, many reasons might cause a node not to forward packages for others such as network congestion or malicious attacks. Therefore, when a node observes that one of its neighbors cannot relay packages for some time, it is more reasonable for the node to cease the communication with that neighbor and keep observing its behavior instead of revoking its key and excluding it from the network immediately. By introducing suspicious behavior, we give nodes that misbehave by accident a chance to return to normal. As a result, our method provides more precise estimation about nodes' behavior than that with a simple binary behavior classification. Fig. 1 demonstrates possible state transitions among different types of nodes in the lifetime of the MANET.

Since nodes' behavior must fall into one of the above three categories, nodes analyze and predict peers' behavior with 3-dimension Dirichlet distribution $\mathsf{Dir}(\alpha_g, \alpha_s, \alpha_m)$, where $(\alpha_g, \alpha_s, \alpha_m)$ is a parameter vector which keeps track of nodes' behavior appearing in sets $\mathbb{B}_g, \mathbb{B}_s$ and $\mathbb{B}_m$, respectively.

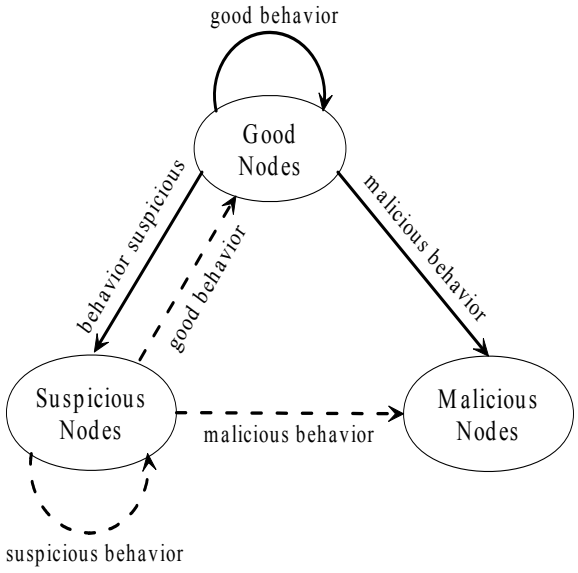


Fig. 1. State Transition Diagram among Different Types of Nodes

After the network initialization phase, each node ID_i is preloaded the following materials:

- **System Parameters**: $\langle q, k, C/\mathbb{F}_q, \mathbb{G}_1, \mathbb{G}_T, e, H, P, P_{pub}\rangle$.
- **Public / Private Key Pair**: $\langle Q_i, d_i\rangle$.
- **Behavior Classification:** $\mathbb{B}_g, \mathbb{B}_s$ and $\mathbb{B}_m$.

C. Step 2. Neighborhood Watch

A neighborhood watch mechanism is a localized monitoring scheme, the main aim of which is to observe behavior of nodes and decide whether they are conformed to descriptions of the MANET protocols. In the neighborhood watch scheme, each node ID_i monitors all its one-hop neighbors and records three categories of behavior each time they occur. We do not limit types of node behavior in this work and any new type of observable behavior can be added to the corresponding set $\mathbb{B}_g, \mathbb{B}_s$ or $\mathbb{B}_m$.

Without loss of generality, we use the notation $\mathcal{N}_i^{(1)}$ to denote the set of one-hop neighbors of node ID_i. Let $N_i^{(1)}$ be the cardinality of the set $\mathcal{N}_i^{(1)}$. Note that $\mathcal{N}_i^{(1)}$, and so $N_i^{(1)}$, will be dynamically changed with time due to the mobility of nodes in the MANET. We use the parameter vector $(\gamma_{j,g}^i, \gamma_{j,s}^i, \gamma_{j,m}^i)$ of 3-dimension Dirichlet distribution to record node ID_i's direct experience with the node ID_j. Initially, the parameter vector is set to $(Ca(\theta_g), Ca(\theta_s), Ca(\theta_m))$, where $(a(\theta_g), a(\theta_s), a(\theta_m))$ is the base rate vector and C is the prior constant (see Section III-B). Node ID_i makes one individual observation for each node $ID_j \in \mathcal{N}_i^{(1)}$ periodically. We set binary variables $\beta_{j,g}^i, \beta_{j,s}^i$ and $\beta_{j,m}^i$ to be 1 if the node ID_i's observation about the node ID_j's behavior is classified into the sets $\mathbb{B}_g, \mathbb{B}_s$ or $\mathbb{B}_m$, respectively, and 0 otherwise. According to new observations about behavior of all its one-hop neighbors, node ID_i first updates its direct experience for each $ID_j \in \mathcal{N}_i^{(1)}$ with the following formulae:

$$\begin{aligned} \gamma_{j,g}^i &:= \mu\gamma_{j,g}^i + \beta_{j,g}^i, \\ \gamma_{j,s}^i &:= \mu\gamma_{j,s}^i + \beta_{j,s}^i, \\ \gamma_{j,m}^i &:= \mu\gamma_{j,m}^i + \beta_{j,m}^i, \end{aligned}$$

where the weight $\mu \in [0, 1]$ is a discount factor for past observations (typically, μ is very close to 1). Node ID_i then updates its own *observation matrix* OM^i with new information. Assume that node ID_i has obtained direct experience with N_i nodes in the network up to the current time instance, node ID_i's observation matrix is as follows:

$$OM^i = \begin{bmatrix} ID_1 & \gamma_{1,g}^i & \gamma_{1,s}^i & \gamma_{1,m}^i \\ \vdots & \vdots & \vdots & \vdots \\ ID_{N_i^{(1)}} & \gamma_{N_i^{(1)},g}^i & \gamma_{N_i^{(1)},s}^i & \gamma_{N_i^{(1)},m}^i \\ \vdots & \vdots & \vdots & \vdots \\ ID_{N_i} & \gamma_{N_i,g}^i & \gamma_{N_i,s}^i & \gamma_{N_i,m}^i \end{bmatrix}.$$

We use the parameter vector $(\alpha_{j,g}^i, \alpha_{j,s}^i, \alpha_{j,m}^i)$ of 3-dimension Dirichlet distribution to keep track of node ID_i's global knowledge about node ID_j's behavior. Note that the vector $(\alpha_{j,g}^i, \alpha_{j,s}^i, \alpha_{j,m}^i)$ will be updated by both node ID_i's direct experience and reports from other nodes. Initially, the parameter vector is also set to $(Ca(\theta_g), Ca(\theta_s), Ca(\theta_m))$. After node ID_i makes a direct observation about node ID_j's

behavior, its global knowledge about node ID_j's behavior will be updated with the following formulae:

$$\alpha^i_{j,g} := \mu\alpha^i_{j,g} + \beta^i_{j,g}, \quad (2)$$
$$\alpha^i_{j,s} := \mu\alpha^i_{j,s} + \beta^i_{j,s}, \quad (3)$$
$$\alpha^i_{j,m} := \mu\alpha^i_{j,m} + \beta^i_{j,m}. \quad (4)$$

Upon obtaining new information about all its one-hop neighbors, node ID_i also updates corresponding rows in its *node status matrix*, NSM^i, which indicates node ID_i's opinion about key status of other nodes. Let N be the total number of nodes in the MANET. Furthermore, we assume that node ID_i has obtained the knowledge of key status of M_i nodes until the current time instance by observing its one-hop neighbors and collecting information from others. Without loss the generality, we also assume that the first $N_i^{(1)}$ rows of NSM^i include information of node ID_i's one-hop neighbors at current time instance. Under the above assumptions, node ID_i's *node status matrix* NSM^i is as follows:

$$NSM^i = \begin{bmatrix} ID_1 & (t^i_1, v^i_1) & R^i_1 & \alpha^i_{1,g} & \alpha^i_{1,s} & \alpha^i_{1,m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ID_{N_i^{(1)}} & (t^i_{N_i^{(1)}}, v^i_{N_i^{(1)}}) & R^i_{N_i^{(1)}} & \alpha^i_{N_i^{(1)},g} & \alpha^i_{N_i^{(1)},s} & \alpha^i_{N_i^{(1)},m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ID_{M_i} & (t^i_{M_i}, v^i_{M_i}) & R^i_{M_i} & \alpha^i_{M_i,g} & \alpha^i_{M_i,s} & \alpha^i_{M_i,m} \\ ID_{M_i+1} & ? & ? & Ca(\theta_g) & Ca(\theta_s) & Ca(\theta_m) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ID_N & ? & ? & Ca(\theta_g) & Ca(\theta_s) & Ca(\theta_m) \end{bmatrix},$$

where t^i_j and v^i_j represent the expiry date and the version number of the current public key Q_j of the node ID_j, respectively. $R^i_j \in \{-1, 0, 1\}$ denotes key status of node ID_j from the point of view of node ID_i, and "?" means node ID_i does not obtain any information about behavior of nodes $ID_k, k \in \{M_i + 1, \ldots, N\}$ until the current time instance. Note that R^i_j being -1, 0 or 1 indicates that the status of node ID_j's key is "Revoked", "Suspicious" or "Trustworthy", respectively. After each node ID_i updates the first $N_i^{(1)}$ rows of NSM^i with the neighborhood watch scheme, it will use the method described in Section V-F to decide whether key status of its one-hop neighbors need to be changed. For nodes whose key status have been marked as "Suspicious", node ID_i will cease the communication with those nodes. Furthermore, node ID_i also keeps observing behavior of suspicious nodes and receiving other nodes' reports to make further decisions.

D. Step 3. Authenticated Information Dissemination

Periodically, node ID_i securely disseminates its direct experience about other nodes' behavior to all its m-hop neighbors. Let $\mathcal{N}_i^{(m)}$ be the set of m-hop neighbors of node ID_i. Node ID_i then sends its observation matrix OM^i to each node $ID_j \in \mathcal{N}_i^{(m)}$ with the following format:

$$om^i_j = ((ID_i, ID_j, OM^i), h_{K_{i,j}}((ID_i, ID_j, OM^i))),$$

where $K_{i,j}$ is the pre-shared key between a pair of nodes ID_i and ID_j, and $h_{K_{i,j}}(\cdot)$ is a secure hash function taking $K_{i,j}$ as the input key. With the aid of the cryptographic pairing (see Section III-A), the pre-shared key $K_{i,j}$ can be separately calculated by nodes ID_i and ID_j in a non-interactive fashion during the phase of a neighbor discovery as follows:

$$K_{i,j} = e(d_i, Q_j) = e(sQ_i, Q_j) = e(Q_i, sQ_j) = e(Q_i, d_j),$$

where $\langle Q_i, d_i\rangle$ and $\langle Q_j, d_j\rangle$ are the public/private key pair of nodes ID_i and ID_j, respectively. Furthermore, both data integrity and authenticity of messages are simultaneously guaranteed by the keyed-hash function $h_{K_{i,j}}(\cdot)$. Therefore, an attacker cannot change content of the observation matrix.

Note that we directly use the pairwise pre-shared secret key $K_{i,j}$ to secure communications among nodes in order to eliminate the communication overhead of establishing session keys. Although we can also use the lightweight ID-based key exchange protocol proposed in [11] to generate a different session key for each interaction, we need three-round communications between two nodes in this case.

E. Step 4. Filter of False Statements

Each time node ID_i receives an observation matrix om^j_i from node ID_j, node ID_i will perform the following information processing and integration algorithm shown in Fig. 2.

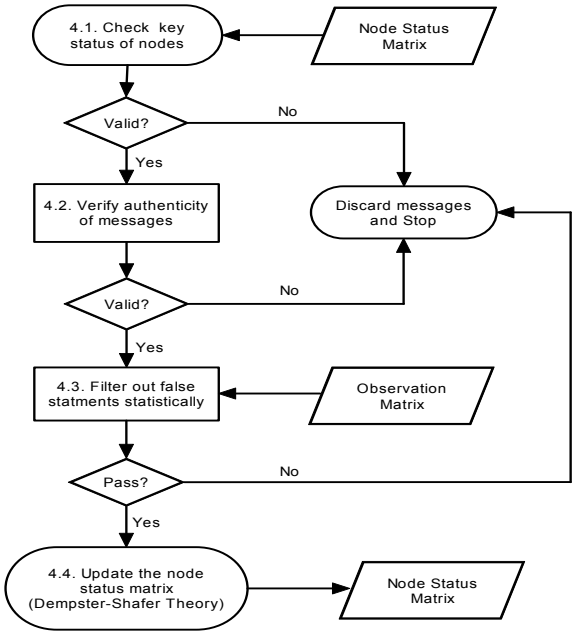


Fig. 2. Information Processing and Integration Algorithm

In Step 4.1, node ID_i checks the status of node ID_j's key in the node status matrix NSM^i. If $R^i_j = 1$, then node ID_i considers node ID_j to be trustworthy and continues the next step; otherwise node ID_i will discard the observation matrix received from node ID_j and stop.

In Step 4.2, node ID_i verifies the authenticity of the message om^j_i using the pre-shared key $K_{i,j}$, as described in Section V-D. If the message passes the authentication, node ID_i will further analyze reliability of node ID_j's observation

in Step 4.3, otherwise node ID_i knows that the received message does not come from node ID_j, and therefore just discards it and stops.

Due to the possibility that nodes are compromised and then arbitrarily report their observations under the control of attackers, messages that node ID_i receives from its counterparts might be spurious. Therefore, the main purpose of Step 4.3 is to avoid or mitigate the influence of false statements from malicious nodes to some degree. In the context of key revocation, attackers' goals are twofold by manipulating observations of compromised nodes. On the one hand, attackers can choose one or many good nodes and report unfairly negative observations about victims' behavior in order to revoke their keys. On the other hand, if attackers know each other and collude in MANETs, they will also propagate unfairly positive observations about their confederates' behavior for the purpose of keeping their keys valid and further damaging the operation of the network. Two efficient statistical filtering techniques based on Beta distribution have been proposed to protect Bayesian reputation systems from liars by Whitby *et al.* [27] and Buchegger *et al.* [6], [7], respectively. Their methods are based on the assumption that the statistical pattern of dishonest reports is different from that of truthful ones. In addition, the difference between these two techniques is that Whitby *et al.*'s method uses quantiles of Beta distribution, whereas Buchegger *et al.*'s method employs a deviation test for the compatibility of received messages. Since our key revocation scheme is based on the Dirichlet distribution and it is difficult to define the quantile in the multivariate case, we only generalize the idea of the deviation test suggested by Buchegger *et al.* [6], [7] to Dirichlet multinomial model in this work.

In Step 4.3, node ID_i extracts orderly each row from the node ID_j's observation matrix OM^j and performs a deviation test for the compatibility of node ID_j's observations. More specifically, when node ID_i extracts the k-th row from OM^j, it computes the following two posteriori expected probabilities with which node ID_k shows behavior in $\mathbb{B}_s$ and $\mathbb{B}_m$, respectively:

$$\begin{aligned}\mathbb{E}\left(p(\theta_s) \mid \vec{\gamma}_k^j, \vec{a}\right) &= \frac{\gamma_{k,s}^j + Ca(\theta_s)}{C + \gamma_{k,g}^j + \gamma_{k,s}^j + \gamma_{k,m}^j},\\ \mathbb{E}\left(p(\theta_m) \mid \vec{\gamma}_k^j, \vec{a}\right) &= \frac{\gamma_{k,m}^j + Ca(\theta_m)}{C + \gamma_{k,g}^j + \gamma_{k,s}^j + \gamma_{k,m}^j},\end{aligned}$$

where $\vec{\gamma}_k^j = \left(\gamma_{k,g}^j, \gamma_{k,s}^j, \gamma_{k,m}^j\right)$ represents node ID_j's direct experience about node ID_k's behavior, and $\vec{a} = (a(\theta_g), a(\theta_s), a(\theta_m))$ is the default base rate vector. And then, node ID_i takes the row corresponding to node ID_k from its node status matrix NSM^i and separately calculates two expected probabilities based on its own knowledge about node ID_k's behavior as follows:

$$\begin{aligned}\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^i, \vec{a}\right) &= \frac{\alpha_{k,s}^i + Ca(\theta_s)}{C + \alpha_{k,g}^i + \alpha_{k,s}^i + \alpha_{k,m}^i},\\ \mathbb{E}\left(p(\theta_m) \mid \vec{\alpha}_k^i, \vec{a}\right) &= \frac{\alpha_{k,m}^i + Ca(\theta_m)}{C + \alpha_{k,g}^i + \alpha_{k,s}^i + \alpha_{k,m}^i},\end{aligned}$$

where $\vec{\alpha}_k^i = \left(\alpha_{k,g}^i, \alpha_{k,s}^i, \alpha_{k,m}^i\right)$ denotes node ID_i's global knowledge about node ID_k's behavior. After obtaining the above four expected probabilities, node ID_i executes the following deviation tests:

$$\begin{aligned}\left|\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^i, \vec{a}\right) - \mathbb{E}\left(p(\theta_s) \mid \vec{\gamma}_k^j, \vec{a}\right)\right| &\leq \varepsilon_1,\\ \left|\mathbb{E}\left(p(\theta_m) \mid \vec{\alpha}_k^i, \vec{a}\right) - \mathbb{E}\left(p(\theta_m) \mid \vec{\gamma}_k^j, \vec{a}\right)\right| &\leq \varepsilon_2,\end{aligned}$$

where $\varepsilon_1, \varepsilon_2 \in (0, 1)$ are two deviation thresholds determined by a system designer. If node ID_j's report about node ID_k's behavior cannot pass the above deviation tests, node ID_i considers that report as incompatible and just discards it. Otherwise, node ID_i uses node ID_j's report to update its knowledge about the behavior of the node ID_k in Step 4.4.

Note that the simplistic information integration method used in [7] is vulnerable to false statement attacks from an adversary, as analyzed theoretically in [22]. Therefore, we set up the second defense line to thwart false statement attacks by integrating other nodes' reports based on Dampster-Shafer belief theory [25]. In [13], Jøsang constructed a bijective mapping between Dirichlet distributions and Dampster-Shafer belief functions. Therefore, we first map node ID_i's global knowledge and node ID_j's report about node ID_k's behavior (two Dirichlet distributions) to two belief distribution functions, respectively. Then we use the technique of belief discounting [14] to update node ID_i's opinion about node ID_k's behavior as a result of node ID_j's report. Finally we map the resulting belief function to a Dirichlet distribution. In this way, the reports from different nodes are given different weight based on their respective reputation. Suppose that

$$\nu = \frac{C\alpha_{j,g}^i}{\left(C + \alpha_{j,s}^i + \alpha_{j,m}^i\right)\left(C + \gamma_{k,g}^j + \gamma_{k,s}^j + \gamma_{k,m}^j\right) + C\alpha_{j,g}^i}.$$

Then node ID_i uses node ID_j's report to update its global knowledge about node ID_k's behavior with the following equations:

$$\begin{aligned}\alpha_{k,g}^i &:= \mu\alpha_{k,g}^i + \nu\gamma_{k,g}^j,\\ \alpha_{k,s}^i &:= \mu\alpha_{k,s}^i + \nu\gamma_{k,s}^j,\\ \alpha_{k,m}^i &:= \mu\alpha_{k,m}^i + \nu\gamma_{k,m}^j.\end{aligned}$$

F. Step 5. Multilevel Response for Malicious Nodes

Each time node ID_i updates its knowledge about node ID_k's behavior in the MANET by either the neighborhood watch scheme or other nodes' reports, it checks whether ID_k's behavior are still within boundaries of its misbehavior tolerance and the status of node ID_k's key needs to be changed. Note that node ID_k's key status R_k^i in the node status matrix NSM^i directly determines how node ID_i treats node ID_k.

To minimize the squared-error loss for the deviation from the true probabilities $p(\theta_m)$ and $p(\theta_s)$ with which node ID_k shows respectively malicious and suspicious behavior, we choose posteriori expected probabilities $\mathbb{E}\left(p(\theta_m) \mid \vec{\alpha}_k^i, \vec{a}\right)$ and $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^i, \vec{a}\right)$ as estimators as usually done. As soon as

node ID_i obtains the updated vector $\vec{\alpha}_k^i$ describing node ID_k's behavior, it will response as follows:

1. Node ID_i computes the posteriori expected probability $\mathbb{E}\left(p(\theta_m) \mid \vec{\alpha}_k^i, \vec{a}\right)$. If $\mathbb{E}\left(p(\theta_m) \mid \vec{\alpha}_k^i, \vec{a}\right) \geq t_{rev}$, i.e., it is equal to or larger than a predetermined revocation threshold t_{rev}, node ID_i sets $R_k^i = -1$ and stops. Otherwise it goes to the next step. Here, $R_k^i = -1$ denotes that node ID_i believes that node ID_k has been compromised and revokes its key. Once node ID_i revokes node ID_k's key, it will cease any communication with node ID_k until node ID_k receives a new key from the TTP.
2. Node ID_i calculates the posteriori expected probability $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^i, \vec{a}\right)$. If $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^i, \vec{a}\right) \geq t_{sus}^k$, i.e., it is equal to or larger than a predetermined suspicion threshold t_{sus}^k, node ID_i sets $R_k^i = 0$. Note that $R_k^i = 0$ means that node ID_i suspects that node ID_k has been compromised, and so node ID_i will shield itself against suspicious behavior of node ID_k by terminating the communication with it. Furthermore, to make further decision, node ID_i continues collecting information to update its knowledge about node ID_k's behavior. Possible state transitions of the suspicious node ID_k are described with dash lines in Fig. 1. Note that three cases might happen for node ID_k: a) Node ID_k just shows suspicious behavior by accident, and therefore behaves normally after a short time. In this case, it will become a good node and be trusted by node ID_i again. b) Node ID_k continues behaving suspiciously. In this case, all nodes will finally mark node ID_k to be suspicious and terminate to communicate with it. Hence, node ID_k will be evicted from the network. c) Node ID_k shows malicious behavior. In this case, the key of node ID_k will be revoked once the posterior expected probability $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^i, \vec{a}\right)$ reaches the revocation threshold. In addition, to react faster than before when node ID_k behaves suspiciously again in the above case a), node ID_i also decreases the suspicion threshold of node ID_k as follows:
$$t_{sus}^k := \xi t_{sus}^k,$$
where $\xi \in (0, 1)$ is a fading factor of the suspicion threshold of a node. Furthermore, we also introduce a parameter t_{max} which denotes the maximum number of state transitions between good nodes and suspicious nodes (see Fig. 1). Once the state transition has appeared t_{max} times for node ID_k, node ID_i will revoke its key immediately by setting $R_k^i = -1$ and terminate any further communication with node ID_k until node ID_k receives a new key from the TTP.

VI. Performance Evaluation

In this section, we evaluate the performance of our key revocation scheme through extensive simulations, the goal of which is to demonstrate attack-resistant properties of our scheme under the existence of independent adversaries and collusive adversaries, respectively. Furthermore, we also show the advantages of classifying nodes' behavior into three categories over the simple binary differentiation.

A. Simulation Setup

we have implemented our key revocation scheme with the C programming language on *Microsoft Visual Studio* platform. The performance evaluations are based on the simulations of 100 wireless nodes that form a MANET over a square (600 m $\times$ 600 m) space and interact 100 times. We use the "random waypoint" model [4] to simulate the mobility of nodes in the MANET. For each node, We set the maximum speed as 10 m/s and maximum travel time as 20 s. The communication range of each node is set to be 100 m. Furthermore, we assume that the base rate vector $\vec{a} = (a(\theta_g), a(\theta_s), a(\theta_m))$ is $(0.6, 0.25, 0.15)$, which denotes the prior uncertainty that honest nodes show good behavior, suspicious behavior and malicious behavior, respectively. We also assume that the discount factor μ is 0.999, both deviation thresholds ε_1 and ε_2 are 0.1, the revocation threshold t_{rev} is 0.2, and the suspicious threshold t_{sus}^k is set to be 0.3. The simulation is repeated for a number of communication sessions. In each session, each node moves to a new position and observe the behavior of its neighbors. Moreover, in some sessions nodes also flood their observations to all m-hop neighbors.

To simulate false statement attacks from adversaries, before running the simulation, we randomly select a certain fraction of the network population as suspicious nodes and malicious nodes, respectively. More specifically, we assume that 20% of all network nodes will show suspicious behavior for different reasons. Among those suspicious nodes, we further assume that half of them, named *type-I suspicious nodes*, show suspicious behavior just by accident (for example, a node drops packages due to the network congestion.) and behave normally after some time (due to the improvements of the network environment), whereas the other half of suspicious nodes, called *type-II suspicious nodes*, show suspicious behavior followed by malicious behavior. Note that type-I suspicious nodes are basically good and therefore record their observations honestly, whereas type-II suspicious nodes are basically malicious and so we assume that they record a suspicious behavior or a malicious behavior with probability $\frac{1}{2}$, respectively, for selected attack objects in each communication session. Considering two types of suspicious nodes in the simulations enables us to demonstrate the following two cases (also see Fig. 1): a) Type-I suspicious nodes can get trustworthy again by good nodes after they are marked as suspicious; b) Keys of type-II suspicious nodes will be finally revoked. Furthermore, we also change the fraction of malicious nodes, ranging from 10% to 30%. Based on the above parameters and assumptions, we simulate two attack scenarios described in Section IV-B.

B. False Statement Attacks by Independent Adversaries

In this section, we evaluate the impact of false statement attacks launched by independent adversaries on our key revocation scheme. In this attack scenario, we further assume that each adversary selects 10% of all network nodes as attack objects, randomly and independently. These adversaries record a malicious behavior for the selected attack objects in each

communication session and flood their accusations to all one-hop neighbors each 5 communication sessions.

Note that we are concerned with the influence of false accusation attacks on good nodes' opinion about the key status of other nodes. Therefore, we randomly sample two good nodes, a type-I suspicious node, a type-II suspicious node, and a malicious node. We then keep track of the opinion of one good node about the key status of other four nodes. Figure 3 shows the attack-resistance properties of our key revocation scheme against independent adversaries when their population increases from 10% to 30%. Although we randomly sample several nodes, we would like to point that the opinion of other good nodes follows the similar curves as Figure 3.

Figure 3(a) describes a good node's opinion about the key status of the other good node. We note that from the point of view of a good node the posterior expected probabilities that the other good node shows suspicious behavior and malicious behavior never exceed the corresponding suspicious threshold and revocation threshold. Therefore, the keys of good nodes never get wrongly revoked by other good nodes under the false statement attacks by independent adversaries.

For a type-I suspicious node, Figure 3(b) shows that from the point of view of a good node the posterior expected probability that a type-I suspicious node shows malicious behavior is always less than the revocation threshold. Hence, the key of the type-I suspicious node will not be revoked unless it have altered their states between good and suspicious for t_{max} times (also see Fig. 1). In particular, when that node show suspicious behavior followed by good behavior, the key of that node will be first marked as suspicious once the posterior expected probability $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^{i,new}, \vec{a}\right)$ exceeds the suspicious threshold. Then that node becomes trustworthy by the good node again after it behaves normally for some time. Note that if one uses the simple binary differentiation for nodes' behavior, the keys of type-I suspicious nodes will be revoked immediately. However, the type-I suspicious nodes only misbehave temporarily and are basically good in our simulations. Therefore, our scheme provides more accurate estimation about nodes' behavior than that in the binary case.

For a type-II suspicious node who show suspicious behavior followed by malicious behavior, Figure 3(c) indicates that a good node will first mark its key as suspicious when the posterior expected probability $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^{i,new}, \vec{a}\right)$ exceeds the suspicious threshold. After gathering enough evidence about malicious behavior of the type-II suspicious node, the good node will finally revoke its key. In addition, Figure 3(d) shows that a good node can correctly revoke the key of a malicious node in the presence of independent adversaries.

From the simulation results in Figure 3, we note that our key revocation scheme can efficiently isolate malicious nodes from the network and also demonstrates strong robustness against the false statement attacks from independent adversaries even in a highly hostile environment (10% type-II suspicious nodes and 30% malicious nodes).

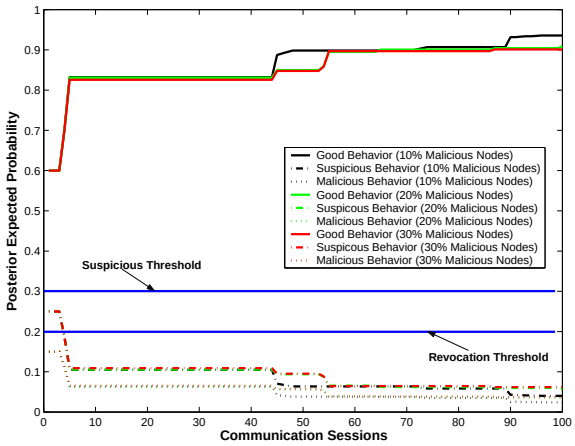
C. False Statement Attacks by Collusive Adversaries

In this section, we study whether false statement attacks from collusive adversaries will affect our key revocation scheme. To this end, we assume that all malicious nodes choose 10% good nodes as common targets instead of randomly and independently selecting attack objects. In this attack scenario, all malicious nodes not only record malicious behavior for the selected 10% good nodes but also record good behavior for other malicious nodes in each communication session. Furthermore, they also propagate their false statements to all one-hop neighbors each 5 communication sessions.

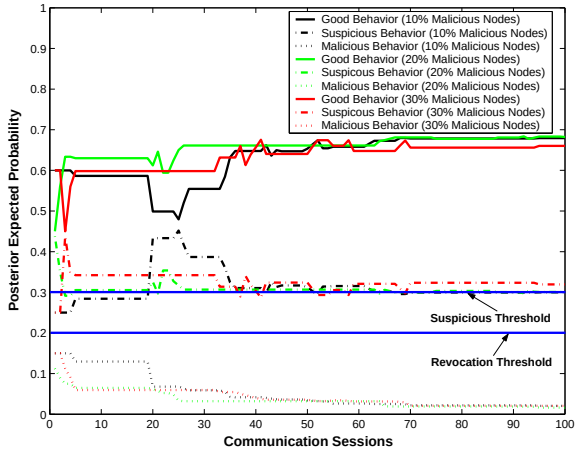
Here, we check the opinion of a good node about the key status of other nodes under the collusive false statement attacks. Similar to the case of independent adversaries, we randomly select two good nodes (one of them is the attack object of the collusive adversaries), a type-I suspicious node, a type-II suspicious node, and a malicious node again, and keep track of the opinion of a good node. Figure 4 shows the attack-resistance properties of our key revocation scheme against collusive adversaries when the number of malicious nodes increases from 10% to 30%. We want to emphasize again that in our key revocation scheme each node has its own view about the key status of other nodes. Although we observe that all good nodes have similar opinion about other nodes' key status in our simulations, it is impossible for us to show all good nodes' opinion due to space limitations. Therefore, we randomly sample several nodes from different categories.

In Figure 4(a), we note that false accusations from collusive adversaries cannot affect the good node's opinion about the key status of the victim they select. The posterior expected probability that the victim shows malicious behavior is always less than the revocation threshold. The reason is that good nodes have accumulated good reputation in the early communication sessions and the false accusations from adversaries cannot pass the deviation test set by good nodes. Therefore, the false accusations will be filtered by good nodes and the keys of good nodes will not be wrongly revoked even in the presence of collusive adversaries.

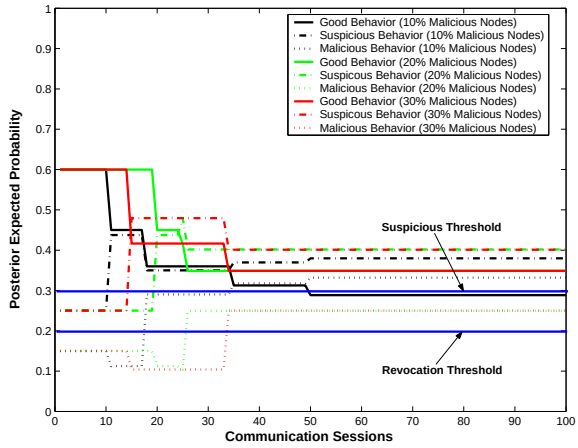
Similar to the case of independent adversaries, Figure 4(b) shows that the key of a type-I suspicious node will not be revoked by the good node unless the number of times that it changes its states between good and suspicious amount to t_{max} (see Fig. 1). Furthermore, if the key of the type-I suspicious node is marked as suspicious due to temporary suspicious behavior, it can be trusted again by a good node after the posterior expected probability $\mathbb{E}\left(p(\theta_s) \mid \vec{\alpha}_k^{i,new}, \vec{a}\right)$ is less than the suspicious threshold. Different from type-I suspicious nodes, malicious behavior of a type-II suspicious node are finally identified by the good node and therefore it will revoke the key of the type-II suspicious node as shown in Figure 4(c). Figure 4(b) and 4(c) demonstrate how a good node responses suspicious behavior in our scheme. While a good node showing suspicious behavior temporarily can get trustworthy again by other good nodes, the real malicious nodes will be evicted from the network. Moreover, false statement attacks from collusive adversaries have no influence on type-I and type-II suspicious nodes since the attack objects



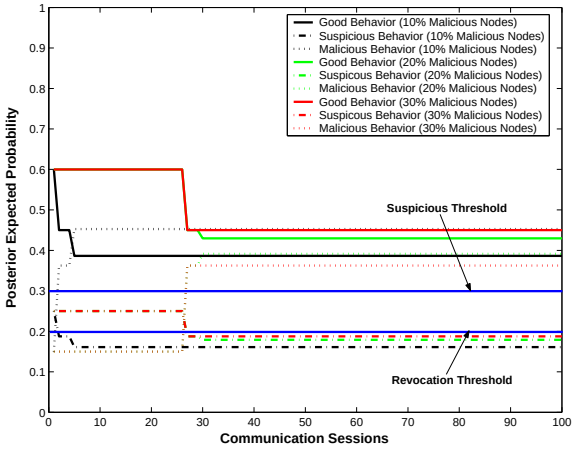
(a) A good node's opinion about the key status of the other good node



(b) A good node's opinion about the key status of a type-I suspicious node



(c) A good node's opinion about the key status of a type-II suspicious node



(d) A good node's opinion about the key status of a malicious node

Fig. 3. Simulation Results for False Statement Attacks by Independent Adversaries

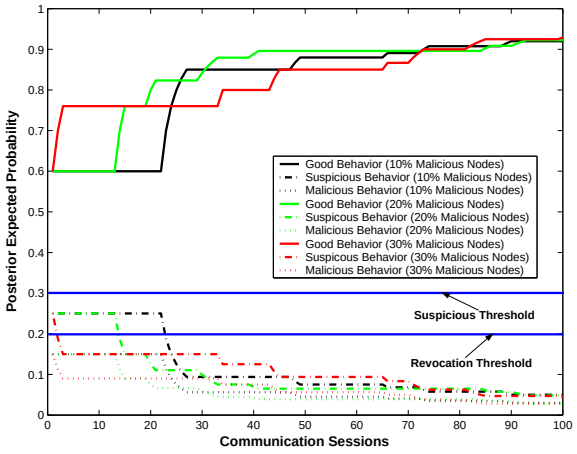
of adversaries are good nodes in our simulations.

Figure 4(d) shows that the key of the malicious node can still be revoked by the good node even if malicious nodes praise each other. The reason is that after the good node have established the bad reputation for the malicious node in the early communication sessions the false praise from the friends of the malicious node is very difficult to pass the deviation test of good nodes. Moreover, even if the false statement can pass the deviation test, this information only has slight influence on the opinion of the good node because of the use of Dampster-Shafter theory (see Section V-E), which gives less weight to the reports from malicious nodes than those from good nodes.

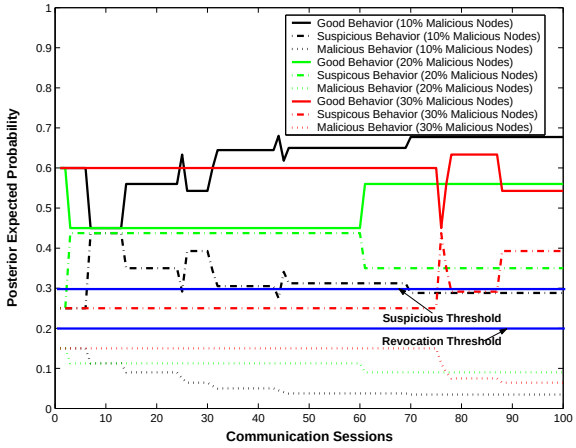
The simulation results in Figure 4 demonstrate that false statements from collusive malicious nodes cannot affect good nodes' opinion about the key status of other nodes. Most false statements are filtered by the deviation tests of good nodes. For those false statements which pass the deviation tests, the information integration technique based on Dampster-Shafter theory guarantees that the false statements only have slight influence on good nodes' opinion. Therefore, our key revocation can still perform well even under the false statement attacks from collusive adversaries.

VII. Conclusion

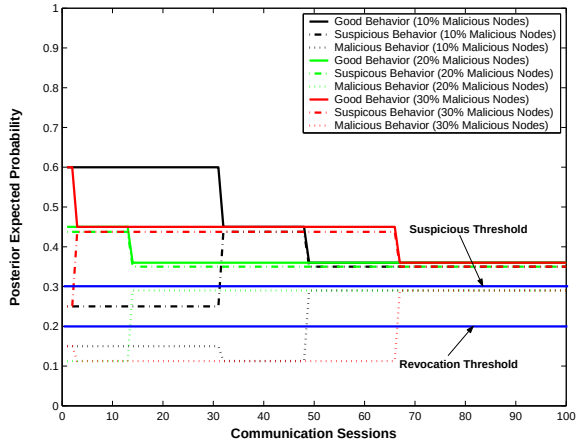
MANETs pose formidable challenges on the issue of key revocation due to lack of infrastructure and centralized servers. This work explores a novel self-organized approach to solve the key revocation problem in MANETs. Firmly rooted in statistics, our key revocation scheme provides a theoretically sound basis for nodes analyzing and predicting peers' behavior based on their own observations and other nodes' reports. Furthermore, classifying nodes' behavior into three categories not only provides network designers more flexibility for various application scenarios, but also enables nodes to make multilevel response according to the severity of malicious behavior. In addition, our key revocation scheme is designed to provide strong defense against false statement attacks from independent and collusive adversaries. The effectiveness and attack-resistance properties of our scheme are confirmed by extensive simulation results.



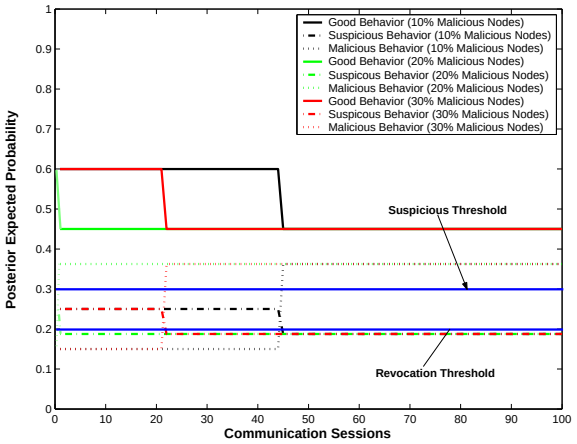
(a) A good node's opinion about the key status of the other good node selected by collusive adversaries



(b) A good node's opinion about the key status of a type-I suspicious node



(c) A good node's opinion about the key status of a type-II suspicious node



(d) A good node's opinion about the key status of a malicious node

Fig. 4. Simulation Results for False Statement Attacks by Collusive Adversaries

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