Monitoring-Based Key Revocation Schemes for Mobile Ad Hoc Networks

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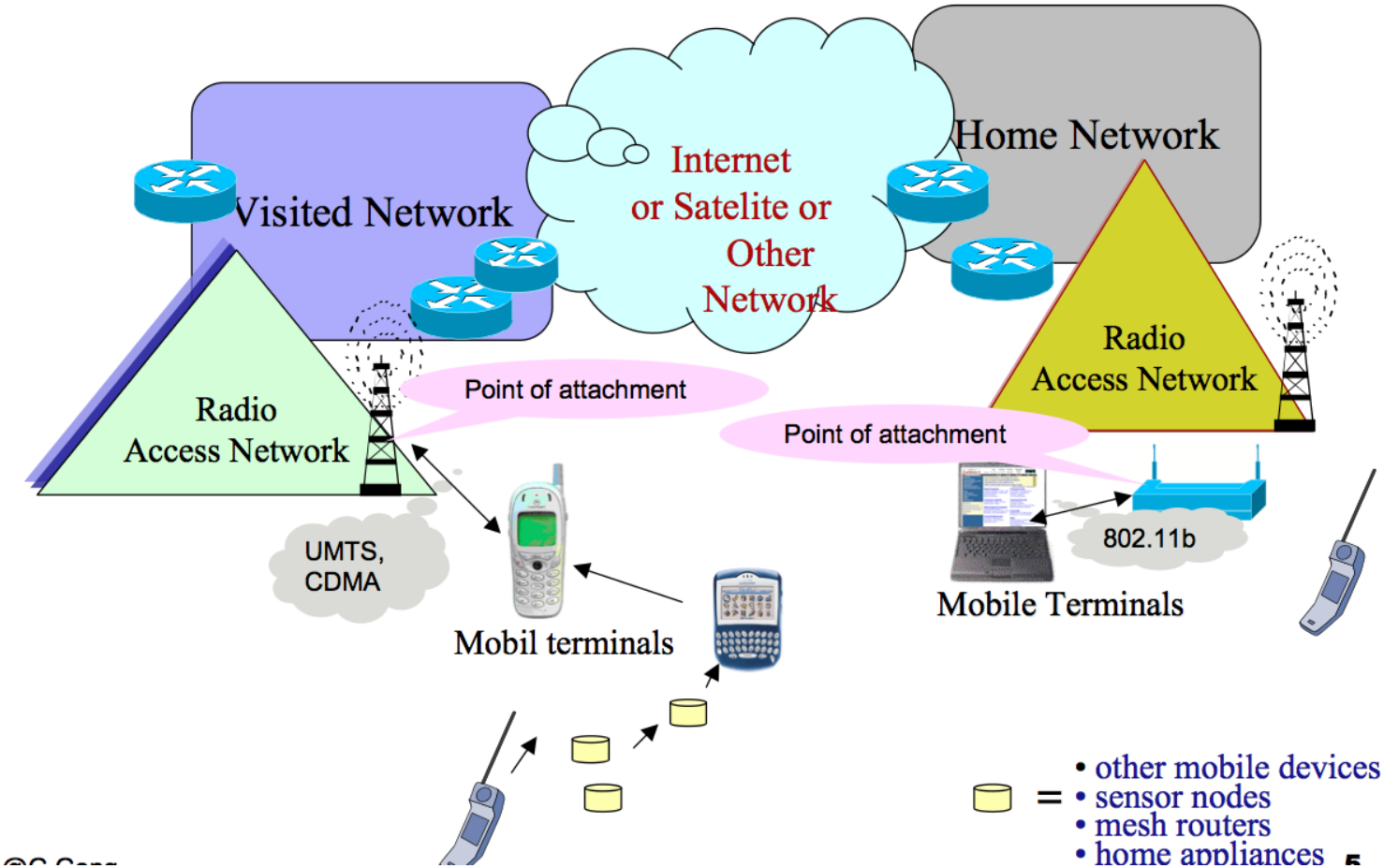
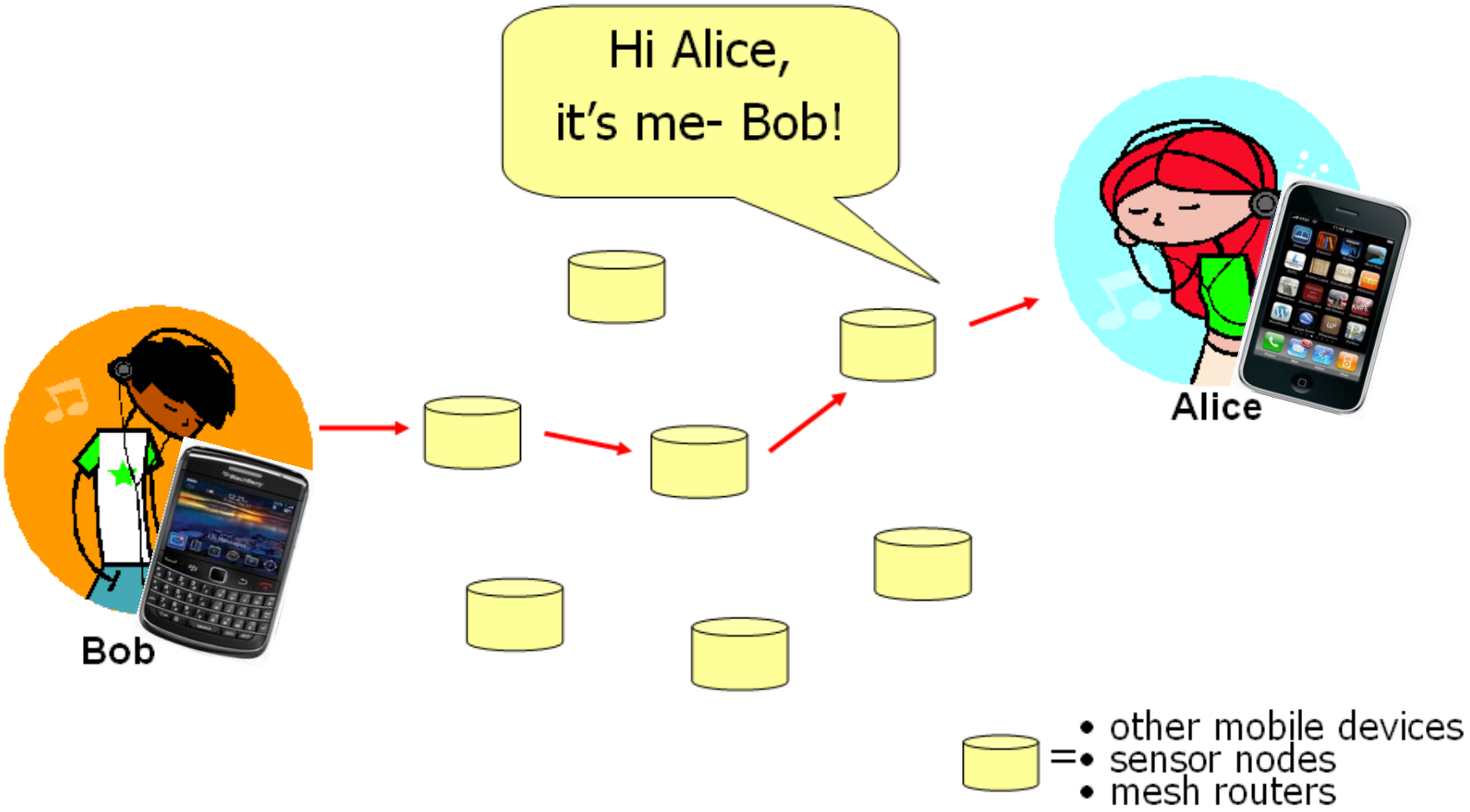
Outline

- **Security** requirements
- Solutions & **challenges** in MANETs
- **Review** of identity-based crypto schemes and existing key revocation schemes
- Two new **monitoring based** self-organized key revocation schemes
- **Implementation** on MICAz motes
- **Conclusions and remarks**

Model for Mobile Communication Security

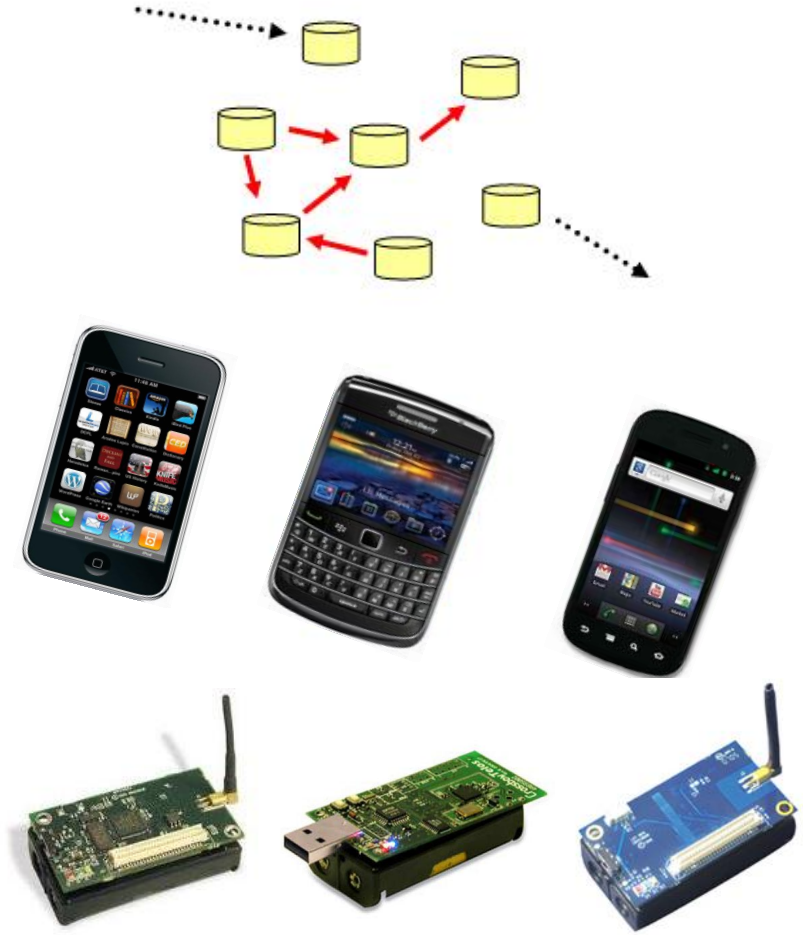


Communication Scenario in MANETs

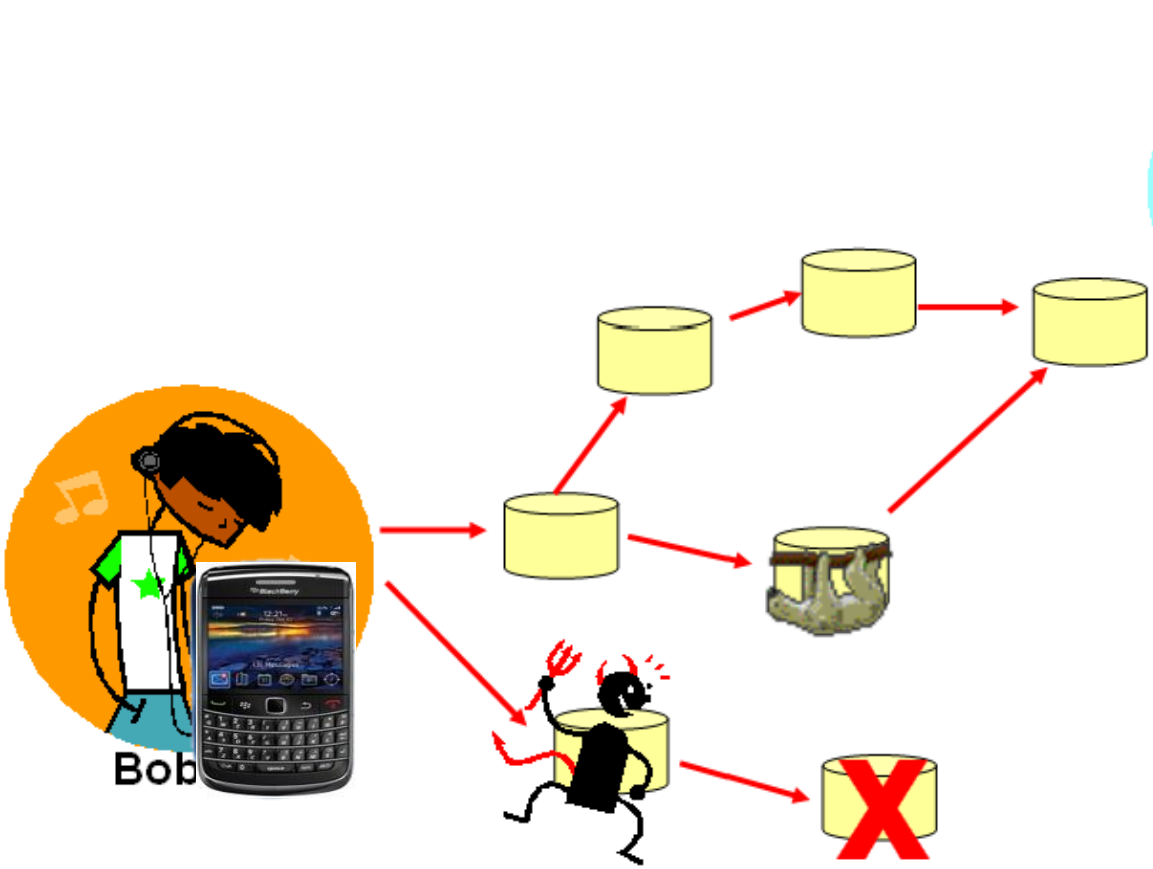


Challenges in MANETs

- Properties of MANETs
  - self-organizing
  - no central trusted third party (TTP)
  - dynamic
  - wireless channels
- Properties of devices
  - constrained devices
    - ▶ CPU, memory, battery
  - limited physical protection

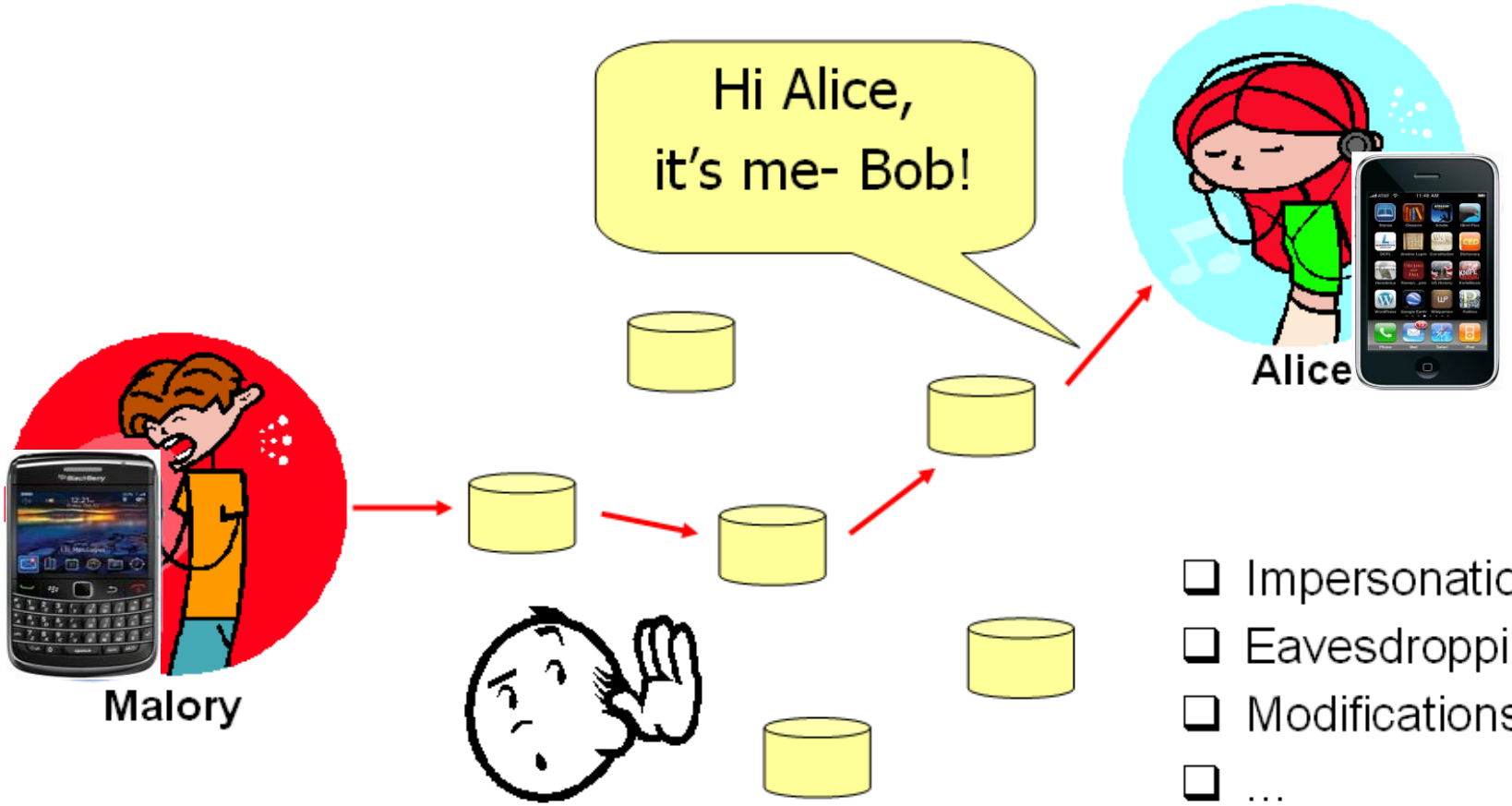


Routing Attacks



- Blackhole/wormhole
- Selfish nodes
- Modification attacks
  - creating loops
  - disruption attacks
- Rushing attacks
- Other DoS attacks

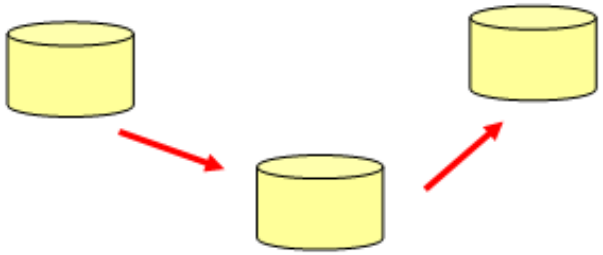
Communication Attacks



- Impersonation
- Eavesdropping
- Modifications
- ...

Security Requirements

- Routing (**hop-to-hop**)
  - source authentication
  - message integrity
- Communication (**end-to-end**)
  - entity authentication
  - message integrity
  - confidentiality



Existing Security Solutions

- **Symmetric-key** schemes
  - require secure key distribution
- **Public key** infrastructures (PKIs)
  - require Certificate Authority (CA) to issue & distribute public key certificates
- **Identity-based** crypto (IBC) schemes
  - require a Key Generation Center (KGC) to generate and distribute **private** keys

We evaluate ID-based solutions! However, the solutions proposed here are applicable to both PKI and d symmetric-key systems.

Review: ID-Based Schemes

- [Shamir'84] First identity-based signature scheme
  - idea: use common information, **"identity" (ID)**, as public keys
  - key generation center (KGC) computes and distributes private keys
- [BF'01] First ID-based encryption scheme
  - Boneh-Franklin scheme uses bilinear mappings
  - set up
    - 2 groups $\mathbb{G}_1, \mathbb{G}_2$ of order q
    - bilinear map $\hat{e} : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_2$
    - arbitrary generator $P \in \mathbb{G}_1$
    - hash function $H_1 : \{0,1\}^* \rightarrow \mathbb{G}_1^*$
  - KGC
    - master key $s \in \mathbb{Z}_q^*$
    - public key $P_{pub} = sP$
  - user ID_i
    - public key $Q_i = H_1(ID_i)$
    - private key $d_i = sQ_i$

Features of ID-Based Schemes

Efficient key management

- no public key certificates
- no key exchange prior communication
- implicit public key validation

$$Q_i = H_1(ID_i \parallel \textbf{'expiry date'})$$

- additionally in pairing based schemes
  - non-interactive pre-shared pairwise keys

$$K_{i,j} = \hat{e}(d_i, Q_j) = \hat{e}(d_j, Q_i)$$

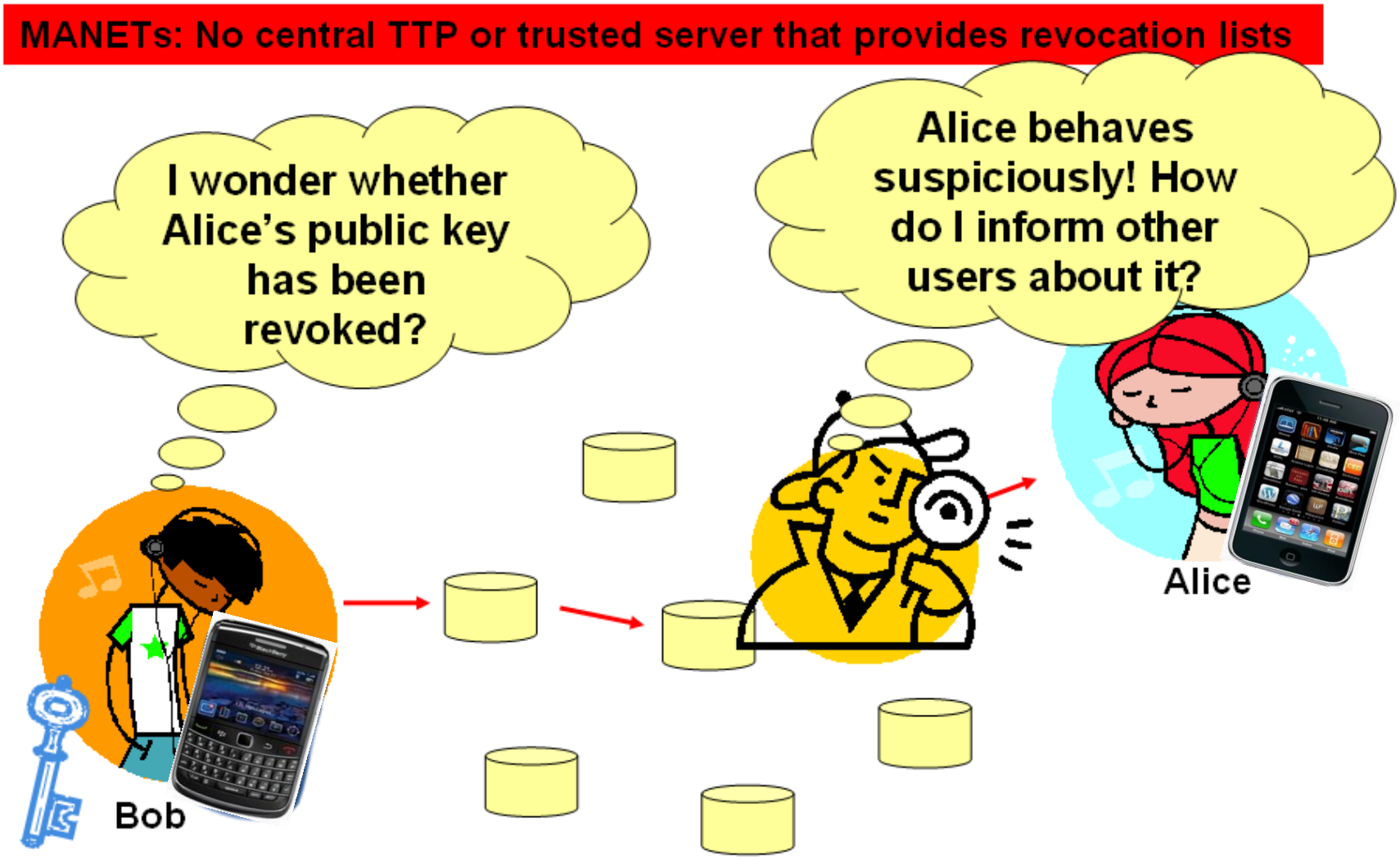
Problems of ID-Based Schemes

1. **Key escrow**
   - inherent property of all ID-based schemes
   - KGC knows all private & pairwise keys

2. **Key revocation**
   - revocation is crucial due to likelihood of compromises
   - no central TTP available to maintain revocation lists
   - current schemes do not provide such mechanisms

3. **Key renewal**
   - after revocation new ID-based keys need to be issued for the same identity

Revocation Problem



Conventional Revocation Schemes

- Certificate Revocation Lists (CRLs)
  - distributed by a central trusted server or TTP to all users
- △CRLs
  - TTP distributes only CRL updates to reduce bandwidth
- Online Certificate Status Protocol (OCSP)
  - users query current certificate status from CA
- Micali's Novomodo scheme
  - new elements of hash chain are published by CA if certificate is still valid, more efficient than OCSP

- **all these solutions work only for PKIs** and require a **fixed infrastructure**, e.g. an on-line CA, TTP or trusted server
- **solutions are not applicable to MANETs!**

Revocation Schemes for MANETs (1)

- **CBC-Based Schemes**
  - **Threshold** based approach [Zhou & Hass '99, Luo et al. '02&'04]
  - **Self-organized** certificate revocation (weighted accusation scheme) [Crépeau et al. '03&'06]
  - **Suicide** for certificate revocation [Clulow & Moore '06&'07]
- **IBC-Based Schemes**
  - **Threshold** based approach [Deng et al. '04, Saxena et al. '04, Zhang et al. '06]

Revocation Schemes for MANETs (2)

- **Game-Theoretical Scheme** [Raya et al.′08]
  - Suitable for **ephemeral** MANETs where contact times between nodes are **short** and neighbors change **frequently** (e.g., VANETs)
  - Reputations are **hard** to build in **ephemeral** MANETS
- **Incentive Based Scheme** [Reidt et al.′09]
  - Encourage rational nodes to sacrifice **short-time** personal utility in favor of **longer term** gains.
  - Inherits the **attractive properties** of suicide-based revocation (i.e., immediacy & abuse resistance)
  - **Reward** a node for a justified suicide by employing a periodically available **Trusted Authority** (TA)

Binary Decision and Multi-level Decisions on Nodes' Behavior

- **Binary decision**: classification of nodes' behavior in all previous schemes: **good** or **bad**.
  - Advantages: simple and easy to implement.
  - Disadvantages:
    - The **binary** behavior differentiation omits the actual **cause** and the **degree** of misbehavior.
    - Some misbehavior may just happen **accidently** and last only for a **short time** (misbehavior due to temporary network congestion, etc.).
- **Multi-level decisions**: classifying nodes behavior into multi-categories of misbehavior.
  - This is a more reasonable **solution**: **collecting more information** about nodes that misbehave accidently instead of evicting them immediately.

Proposed Key Revocation Schemes with Binary and Multi-level Decisions

We consider two scenarios

Binary decisions of misbehavior

$\Downarrow$

Majority voting trust model

Multi-level decision for multi-categories of misbehavior

$\Downarrow$

Dirichlet multinomial model

Pre-Conditions

- **System set-up**:
  1. based on BF scheme
  2. preshared key $K_{i,j}$ provides message authentication, e.g., $f(x)$ where $f(x)$ is a hash function
- **System assumptions**
  1. bidirectional communication links
  2. each node has a monitoring scheme implemented
  3. each node has a unique identity
  4. each node knows identities and hop-distance of its one-hop neighbors
  5. nodes obtain keys from off-line KGC before joining network

Scheme 1: Key Revocation with Binary Decision

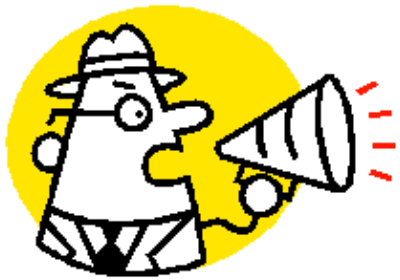
Key Renewal and Key Format

- **Renew key** if previous key is
  - revoked
  - compromised
  - expired

- **New keys issued for same identity**
  - $Q_i = H_1(ID_i \parallel t_i \parallel v_i)$
  - t_i: expiry date of public key Q_i
  - v_i: version number of Q_i
  - user needs to re-authenticate to external KGC

Key Revocation

- **Revocations** need to be on-line
- **Revoke key** if
  1. nodes behave suspiciously
     - observe & tell others
     - send accusation message ***am***
     - δ accusations for revoking key
  2. own key is compromised
     - tell others
     - send harakiri message ***hm***



Neighborhood Watch

All nodes **observe their 1-hop** neighborhood N_i

- each node ID_i maintains **accusation matrix** AM_i consisting of accusation values $a^i_{j,i}$

$$AM^i = \begin{bmatrix} ID_1 & (t^i_1, v^i_1) & a^i_{1,i} \\ \vdots & \vdots & \vdots \\ ID_{N_i} & (t^i_{N_i}, v^i_{N_i}) & a^i_{N_i,i} \end{bmatrix}.$$

  - N_i: a set of the members of 1-hop neighbors
  - $a^i_{j,i} = 0$, ID_i marks ID_j as trustworthy
  - $a^i_{j,i} = 1$, ID_i marks ID_j as malicious, only reset if a new valid key Q'_j is received
  - update AM^i every time malicious behavior is observed

Propagation

- **Accusation** messages ***am***
  - after AM^i or KRL^i update, ID_i propagates update am_i

    $am_{i,j} = (f_{K_{i,j}}(ID_i, am_i), ID_i, am_i)$ **to all** $j \in N_i$

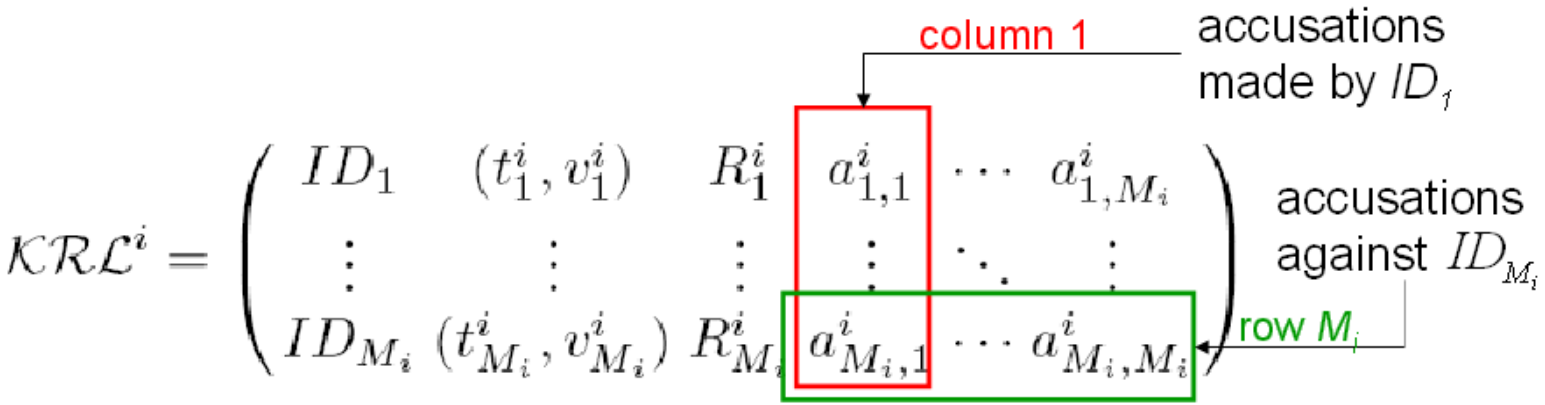
- **Harakiri** messages ***hm***
  - upon noticing that private key d_i is compromised, ID_i broadcasts

    $hm_i = (ID_i, d_i, Q_i, t_i, v_i, \text{“revoke"}, hopcount)$

- **Messages** send to 1-hop neighborhood
  - verify authenticity and forward
  - repeated m times

Accusation Scheme

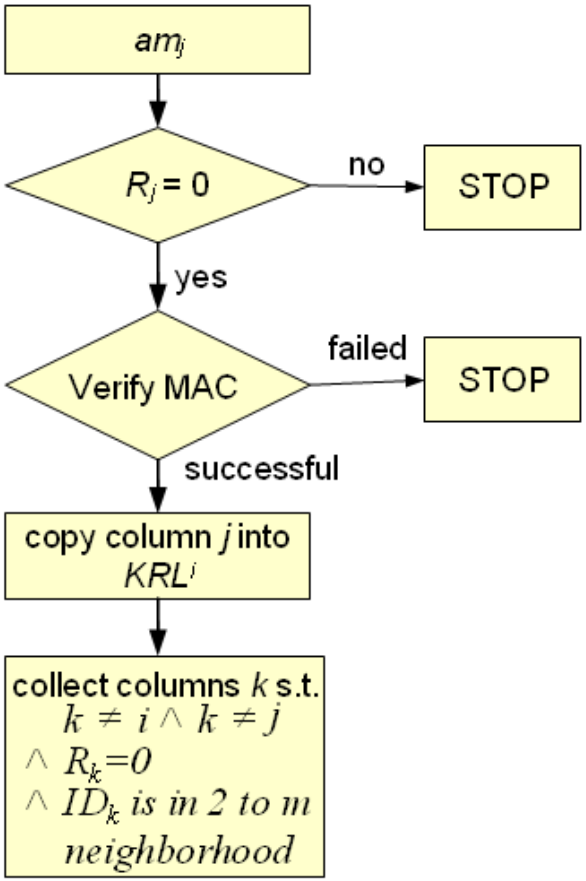
Every node ID_i generates key revocation list KRL^i from its own ***am*** and received ***am & hm***



- M_i number of nodes in m-hop neighborhood
- node i considers the public key Q_j of node j as revoked if revocation value $R_j^i = 1$: $R_j^i = 1$ **if** t_j^i **expired or** $a_{j,i}^i = 1$ **or** $a_{j,j}^i = 1$ **or** $\sum_{k=1}^{M_i} a_{j,k}^i > \delta$
- δ is the threshold for revoking a key

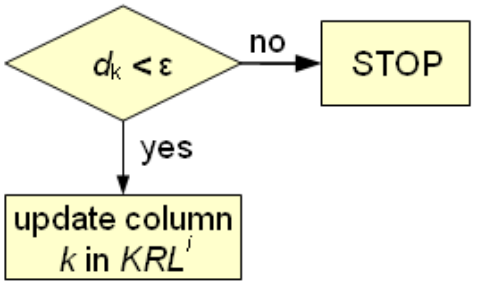
Update Key Revocation List (KRL)

ID_i **repeats** for all received accusation messages am_j



After processing all received am_j

- ID_i checks the number d_k of collected columns k
- ε is threshold for updating columns of nodes that are 2 to m hops away



ID_i **updates column** k **in** KRL^i

$$a^i_{l,k} = \begin{cases} 1 & \text{if } \sum_{j=1}^{d_k} a^j_{l,k} > \frac{d_k}{2} \\ 0 & \text{if } \sum_{j=1}^{d_k} a^j_{l,k} < \frac{d_k}{2} \\ a^i_{l,k} & \text{otherwise} \end{cases}$$

Recap Revocation Scheme

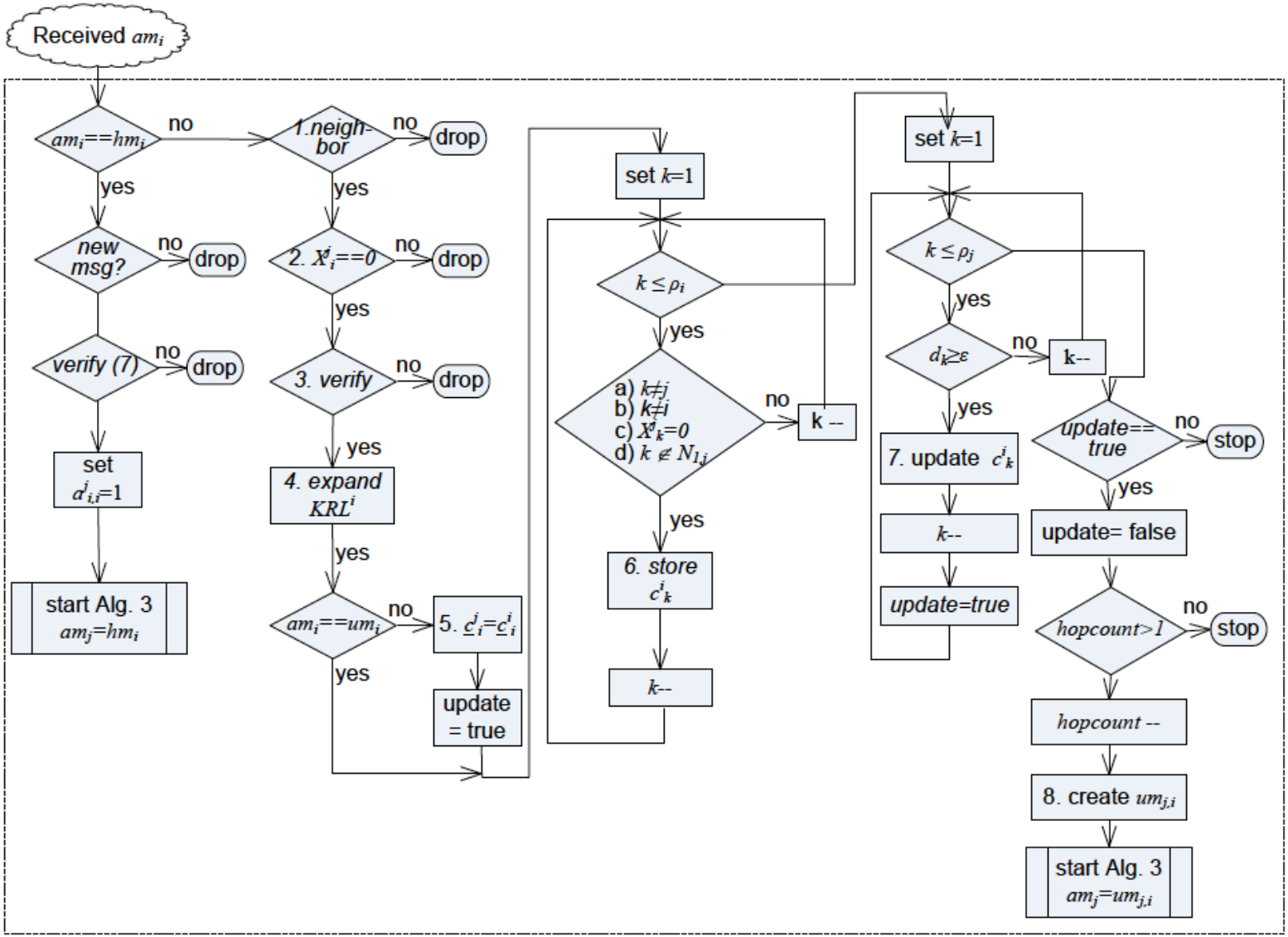
Neighborhood Watch (NW)

Propagation

Accusation Scheme

Harakiri

Flowchart Revocation Algorithm for Update KRL



Security Analysis (1): Outsider Attacks

- Routing attacks prevented by using **secure routing protocols**
- Eavesdropping prevented by using **secure AKE protocols**
- Message authentication and integrity are protected with **pre-shared keys**
- **battery exhaustion attack** prevented by only accepting accusation messages from trusted one-hop neighbors
- If an adversary **spoofs the identity** of a trusted one-hop neighbor, the attack would be detected when verifying the authenticity of the first message.

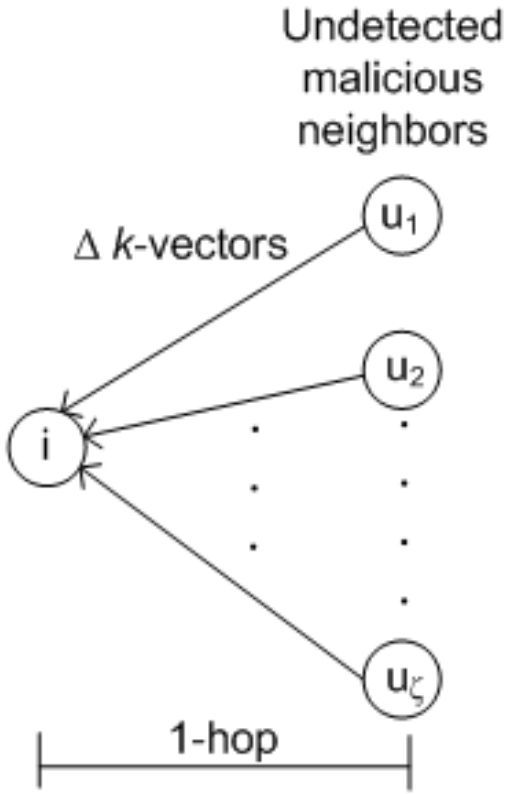
Security Analysis (2): Non-colluding Insiders

- **Sybil Attacks**
  - Malicious nodes could try to bypass security parameter δ by fabricating δ different identities, so called sybil attack.
  - **Sybil attacks requiring keying material** are prevented by using **ID-based public keys** of a fixed format, i.e. upon identifying to the KGC, a node can only obtain one possible valid private key for a specific expiry date.
  - **Sybil attack that does not require keying material** is prevented by choice of security parameters δ and ε.
- **Roaming Adversaries**: By selecting *m* sufficiently large and the expiry intervals small, roaming adversaries have to travel fast to escape the revocation of their keys.

Security Analysis (3): Colluding *l*-hop Neighbors

Colluding one-hop neighbors

- **Monitoring scheme**
  - **false negative rate** β
  - undetected malicious one-hop neighbors $n_u^i = \beta n_m^i$ (n_m^i is the number of i's malicious one-hop neighbors)
- **Altering direct** accusations
  - prevented if $\beta < \frac{\delta}{\sigma_i}$ (σ_i is the sum of i's honest one-hop neighbors and malicious one-hop neighbors)
- **Altering reported** accusations
  - prevented if $\beta < \frac{1}{\sigma_i}(\lfloor \frac{\varepsilon}{2} + 1 \rfloor)$



Scheme 2: Key Revocation in MANETs based on Dirichlet Multinomial Model

- **Model**
  - Suppose that the behavior of network nodes falls into one of **three possible categories**: good, suspicious and malicious behavior.
  - Assume that the observed data are gathered by a **multinomial experiment** and therefore follows a **multinomial distribution**.
  - Use the 3**-dimension Dirichlet distribution** as the **prior distribution** of the unknown probabilities.
  - After obtaining the observation data, compute the **posterior probability expectation** of unknown parameters and make the corresponding response.

Dirichlet-Multinomial

- The **multinomial Dirichlet density function** over Θ is

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

- The **prior constant** $\mathcal{C}$ can be set to $\mathcal{C} = 2$ when a uniform distribution over binary state spaces is assumed.
- $r(\theta_i) + \mathcal{C}a(\theta_i)$ is called the **evidence vector**. $r(\theta_i)$ is the information obtained from the observations and $\mathcal{C}a(\theta_i)$ is the prior uncertainty.
- The **probability expectation** of any of the k random variables can be computed as: $\mathbb{E}(p(\theta_i) \mid \vec{r}, \vec{a}) = \frac{r(\theta_i)+\mathcal{C}a(\theta_i)}{\mathcal{C}+\sum_{i=1}^{k} r(\theta_i)}$.

A New Approach for Key Revocation with Multi-level Decisions in MANETs

Bayesian Model of Node Behavior Analysis:

- Network nodes' behavior falls into one of **three possible categories**.
- The observed data are gathered by a **multinomial experiment**.
- **3-dimension Dirichlet distribution** is used as the **prior distribution** of the unknown probabilities.
- The **posterior probability expectation** of unknown parameters is computed to make the corresponding response.

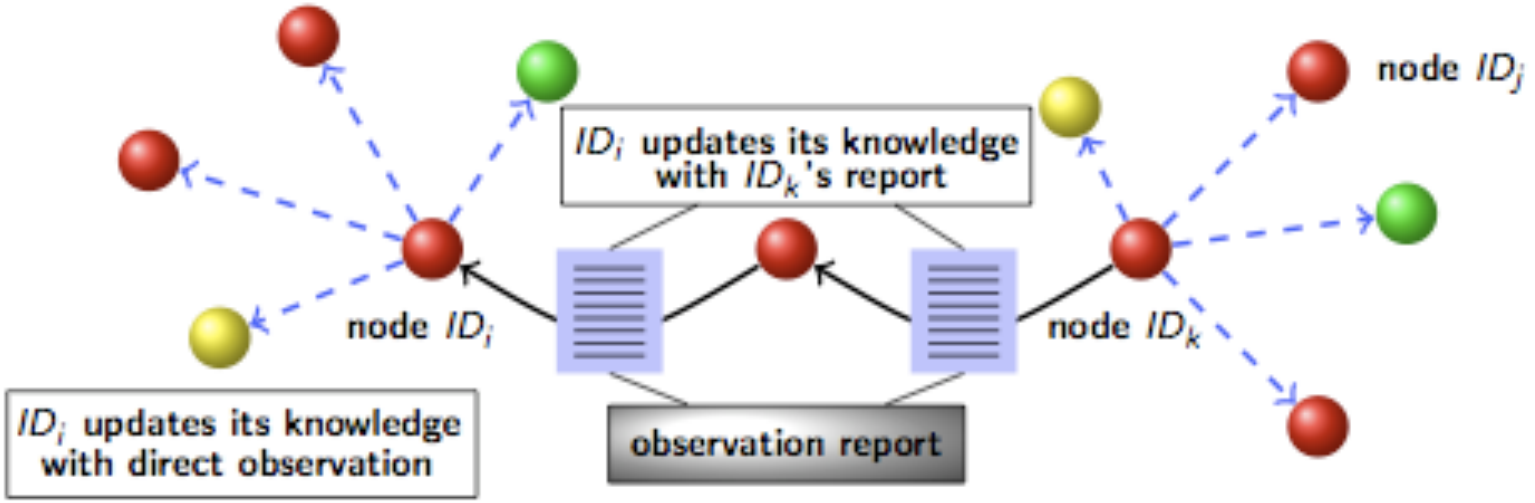


Figure: ID_i updates its knowledge about other nodes' behavior based on its direct observation and ID_k's report

Overview of Protocol

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

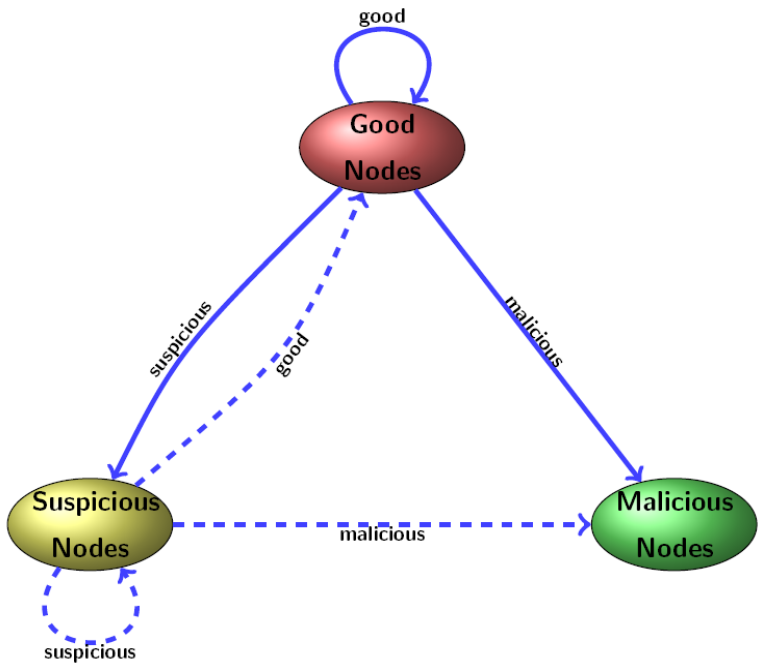
- Filter out potentially false statements statistically
- Update key status of nodes based on Dempster-Shafer theory

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

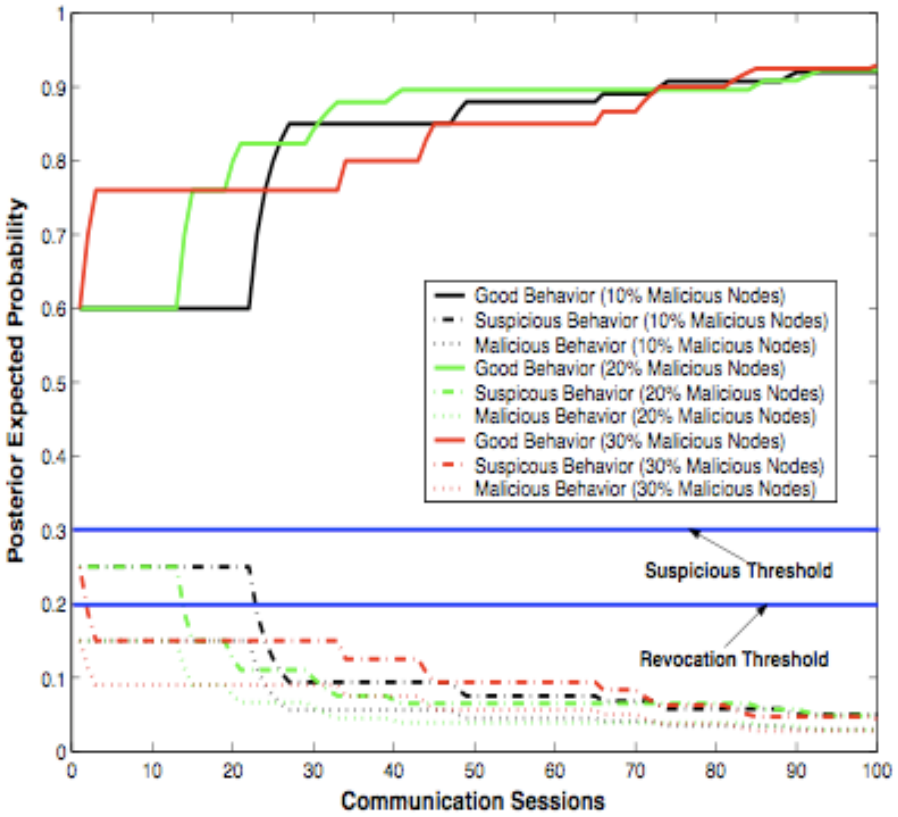
Classification of node behavior

- State space $\Theta = \{\theta_g, \theta_s, \theta_m\}$: θ_g, **good**; θ_s, **suspicious** ; and θ_m, **malicious**
- Three behavior sets: $\mathbb{B}_g$, **good behavior**; $\mathbb{B}_s$, **suspicious behavior**; and $\mathbb{B}_m$, **malicious behavior**
- Node behavior analysis: **3-dimension Dirichlet distribution Dir($\alpha_g, \alpha_m, \alpha_s$)**

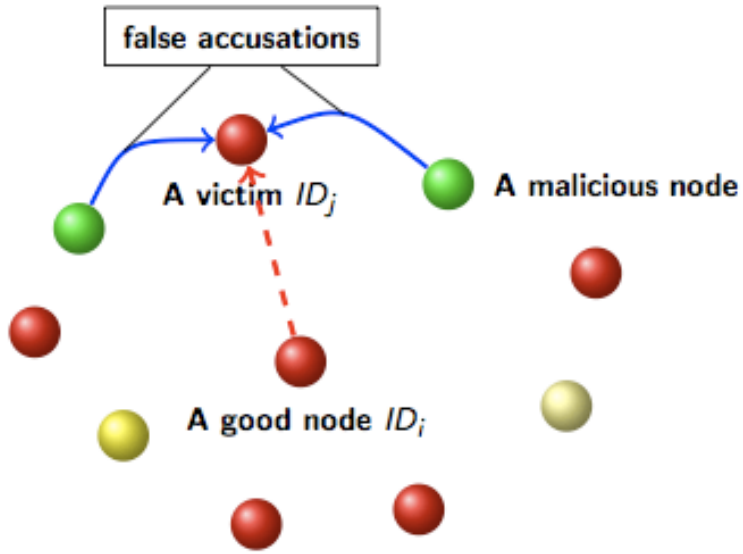


Protocol Simulation and Analysis

False Statement Attacks by Collusive Adversaries (I)

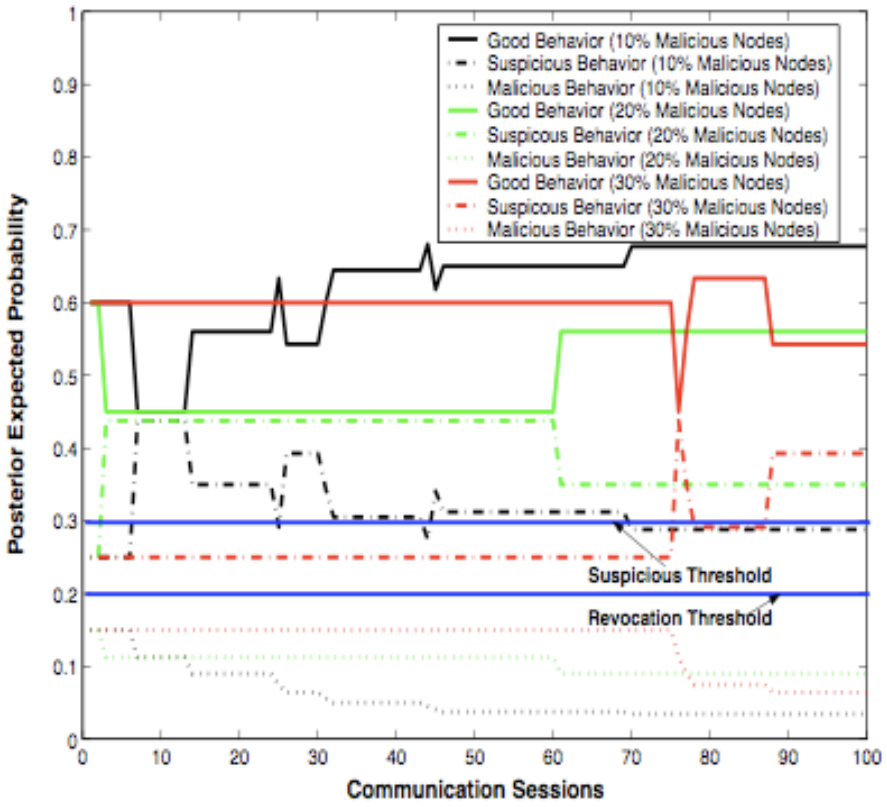


(a) A good node's opinion about the key status of the other good node selected by collusive adversaries

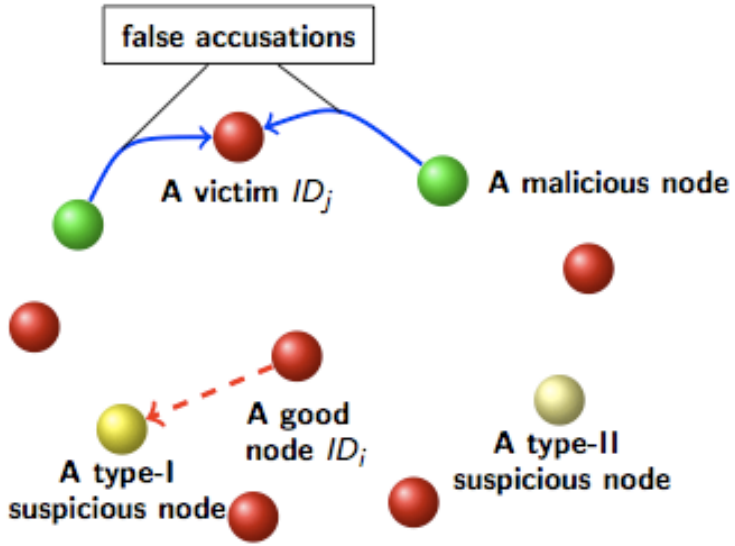


The left figure shows that false accusations from collusive adversaries cannot affect a good node ID_i's opinion about the victim ID_j's behavior.

False Statement Attacks by Collusive Adversaries (II)



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



- A type-I suspicious node shows suspicious behavior followed by good behavior.
- The left figure shows that a type-I suspicious node can be trusted again by a good node ID_i after it behaves normally.

Summary for Scheme 1

Features of the proposed **self-organized** key revocation scheme with binary decision for ID-based schemes employed in MANETs:

- Proposed **revocation scheme** enables user to instantly verify whether a key is revoked and revoke their own keys
- **Revocation scalable in security & performance** in terms of security parameters (δ, ε, m)
- Efficient due to use of **pre-shared asymmetric keys** with MACs and propagation to m-hop neighborhood
- Designed **ID-based key format** allows key renewal

Summary of Scheme 2

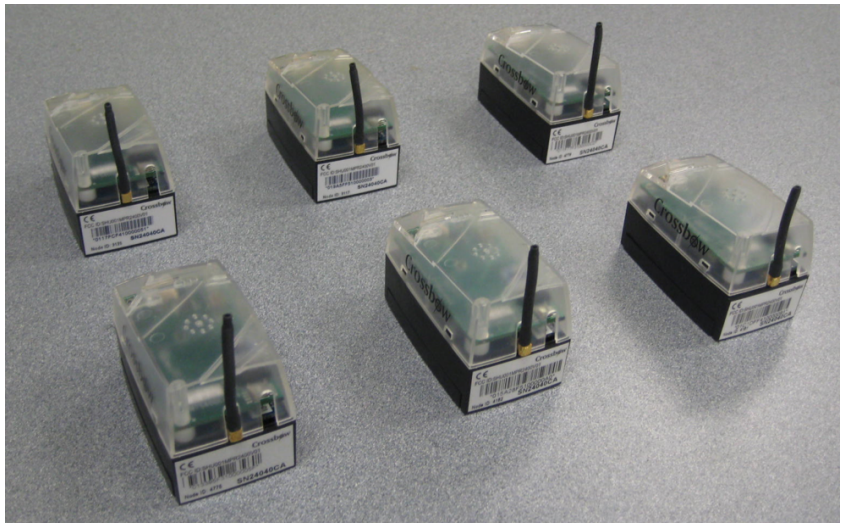
- A novel **self-organized** key revocation scheme based on the **Dirichlet multinomial model** and **identity-based cryptography**
- A **theoretically sound basis** for nodes analyzing and predicting peers' behavior based on their own observations and other nodes' reports
- **Three** categories of nodes' behavior: **good** behavior, **suspicious** behavior, and **malicious** behavior
- **Multilevel response** according to the severity of malicious behavior.
- Good **attack-resistant** properties with appropriate selection of design parameters.

Extensions of the Two Basic Revocation Schemes

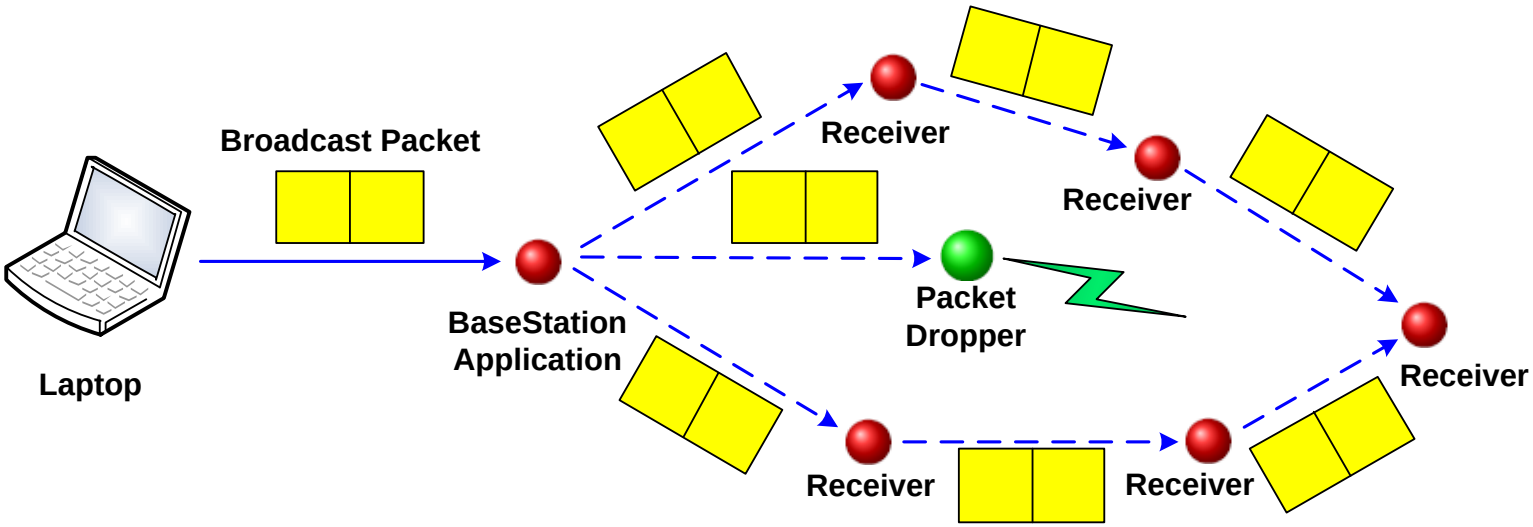
1. **Distributed** On-line KGC
2. Regaining Trust
3. Sleeping Nodes
4. **Confidential** Accusations
5. Dedicated Key Pairs:
6. Crypto Agility: adopt to **PKI or symmetric-key** schemes
7. Adapting Scheme to Hostile Environments
8. **Adaptive** Monitoring Schemes and Security Parameters
9. Network-wide **Revocations**
10. Adversary Models

Experiment Platform

- Sensor node: **MICAz** mote
  - a **low-power** 8-bit microcontroller **ATmega128L**
  - 128 KBytes program flash memory
  - 512 KBytes measurement flash
  - 4 KBytes configuration EEPROM
  - Maximum clock frequency: 8 MHz
  - **ZigBee** transceiver **CC2420** (Data rate: 250 kbps; Packet size: up to 128 bytes (with a payload of 102 bytes))
  - Operation system: **TinyOS**



Experiment Setup (in progress)



- The testbed consists of **one laptop sender** and **seven MICAz motes**.
- The laptop connects to an MICAz mote through a **programming board** and periodically generate a broadcat message.

Experiment Setup Cont. (in progress)

- One of the MICAz motes (the green one) is configured to **drop** the broadcast packet.
- Other motes **record** the behavior of the green one and perform the **key revocation**.
- The **pairwise keys** among sensor nodes are computed using **bilinear pairing** during the **neighborhood discovery** phase.
- The **message authentication code** (MAC) is calculated using a **keyed hash function**.

Implementation of Bilinear Pairing on MICAz Motes (1)

Bilinear pairings for binary elliptic curves:

- A **supersingular** binary curve: $y^2 + y = x^3 + x + b$
- The **order** of this curve is $N = 2^m + 1 \pm 2^{\frac{m+1}{2}}$
- The **embedding degree** is $k = 4$ (i.e., the least integer s.t. N divides $2^{km} - 1$)
- Choosing $T = 2^m - N$ and a prime r dividing N, Barreto *et al.* defined the **reduced η_T pairing**:

$$\begin{aligned} \eta_T(\cdot,\cdot) &: E(\mathbb{F}_{2^m})[r] \times E(\mathbb{F}_{2^m})[r] \to \mathbb{F}^*_{2^{4m}} \\ \eta_T(P,Q) &= f_{T',P'}(\psi(Q))^{\frac{2^{4m}-1}{N}}, \end{aligned}$$

where $T' = \pm T$ and $P' = \pm P$. The function f is a **Miller function** and ψ is the **distortion map** $\psi(x, y) = (x^2 + s, y + sx + t)$.

Implementation of Bilinear Pairing on MICAz Motes (2)

- **Field** representation: $\mathbb{F}_{2^{271}} = \mathbb{F}_2[x]/x^{271} + x^{207} + x^{175} + x^{111} + 1$
- Pairing-friendly **supersingular** curve $E : y^2 + y = x^3 + x$
- Let $q = 2^{271}$. The extension field $\mathbb{F}_{q^4}$ is represented using **tower extensions** $\mathbb{F}_q \to \mathbb{F}_{q^2} \to \mathbb{F}_{q^4}$:
  - $\mathbb{F}_{q^2} = \mathbb{F}_q[s]/(s^2 + s + 1)$,
  - $\mathbb{F}_{q^4} = \mathbb{F}_{q^2}[t]/(t^2 + t + s)$.

  A **basis** for $\mathbb{F}_{q^4}$ over $\mathbb{F}_q$ is $\{1, s, t, st\}$.
- The reduced η_T pairing can be computed within 2.5**s** on MICAz motes.

Pairing Computation on Wireless Sensor Nodes

Table: η_T pairing on different wireless sensor nodes

Implementation	Sensor Nodes	Timing (s)
Szczechowiak *et al.*'08	MICAz	10.96
Ishiguro *et al.*'08		5.80
Szczechowiak *et al.*'09		2.66
Fan & Gong'09		**2.5**
Oliveira *et al.*'10		1.90
Szczechowiak *et al.*'08	Tmote Sky	5.25
Szczechowiak *et al.*'09		1.71
Oliveira *et al.*'10		1.27

The contents of the talk are taken from the following references:

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