One Cell is Enough to Break Tor's Anonymity

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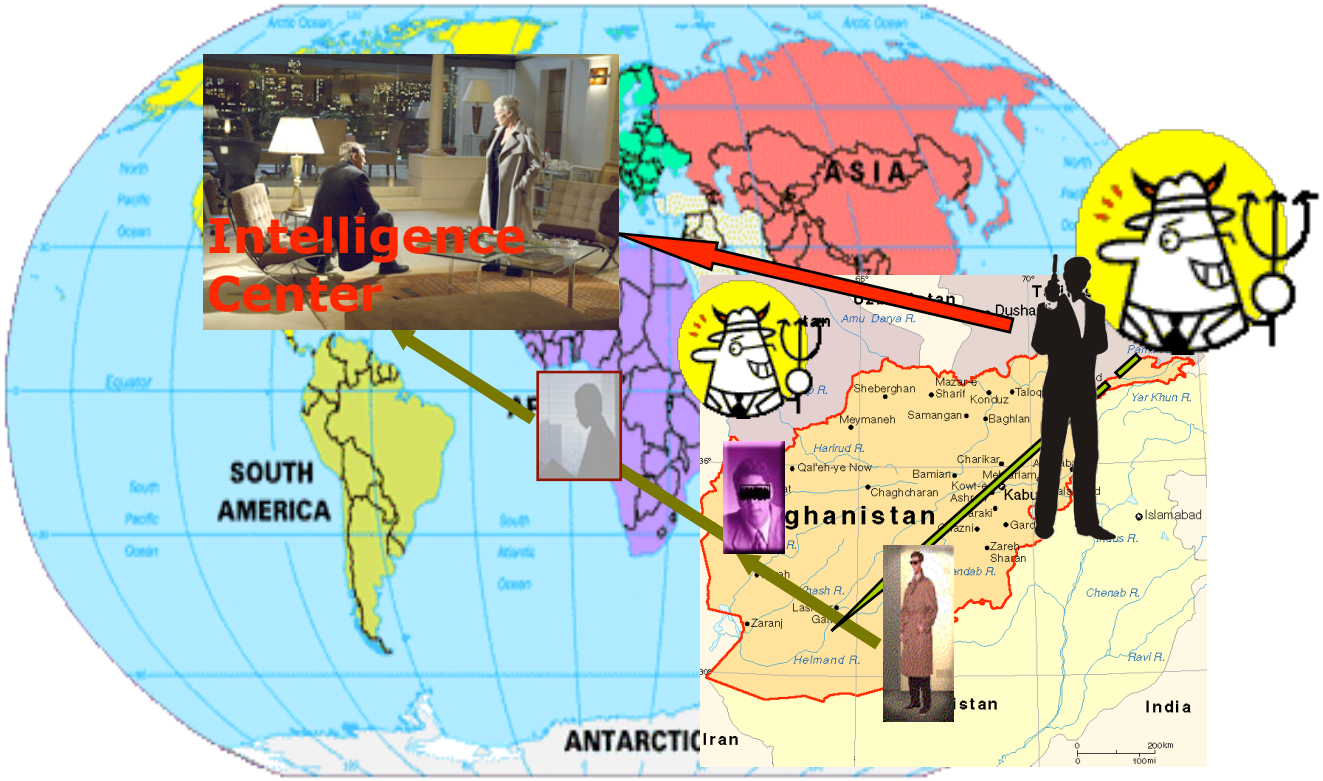
Outline

- Introduction
- Basic components and operation of Tor
- Protocol-level attacks
- Impact of protocol-level attacks
- Guideline of countermeasures
- Related work
- Summary

Internet Security

- Internet has brought convenience to our everyday lives
- Internet has many design vulnerabilities
  - Malicious codes (worm and viruses) caused $13.2 billions in financial losses worldwide in 2001
- We need to understand these attacks and design corresponding countermeasures
- We present our research on a new type of attack against anonymous communication systems

Traditional Spy Network



- Indirectly send secret to Intelligence headquarter through a number of intermediate agents
- Protect the intelligence agent (i.e., source of secret) from being identified

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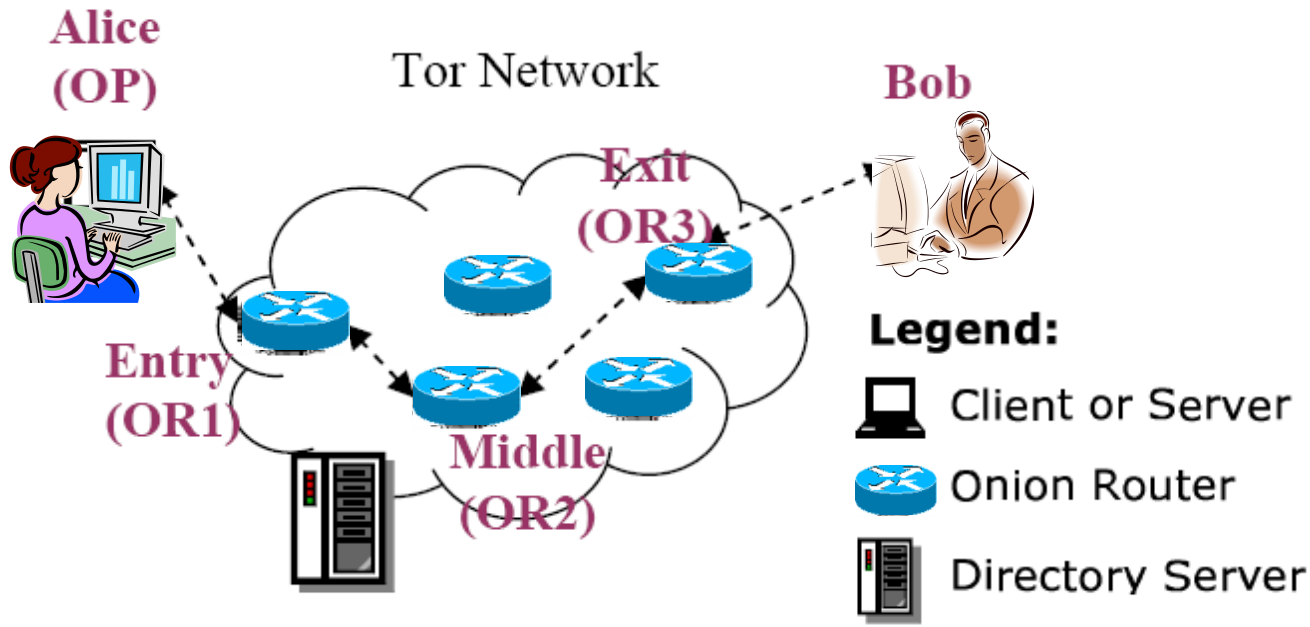
Tor

- A great Internet anonymous communication network
- Volunteer operation model
  - Volunteers around the world donate their computers and network bandwidth
  - Those donated computers form the Tor network based on the Tor protocol
  - Those computers in the Tor network relay user messages down to the destination
- Users of Tor
  - Human rights workers
  - Many others: refer to Tor website https://www.torproject.org/torusers.html.en/

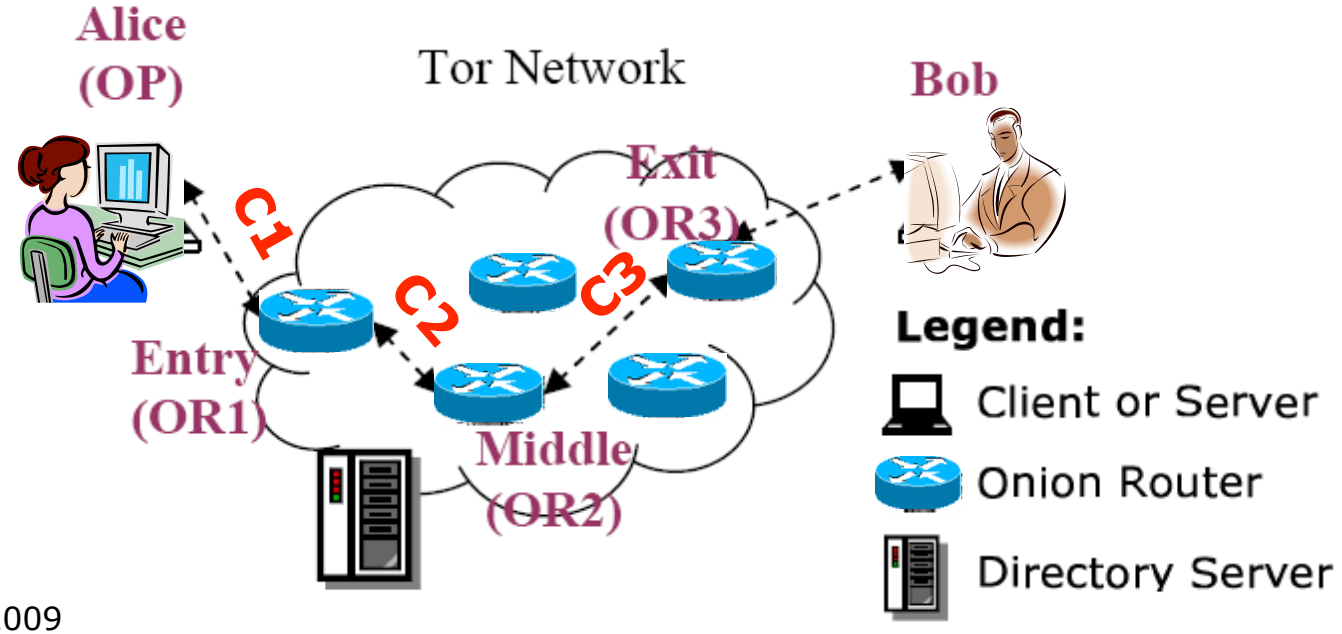
Components of Tor



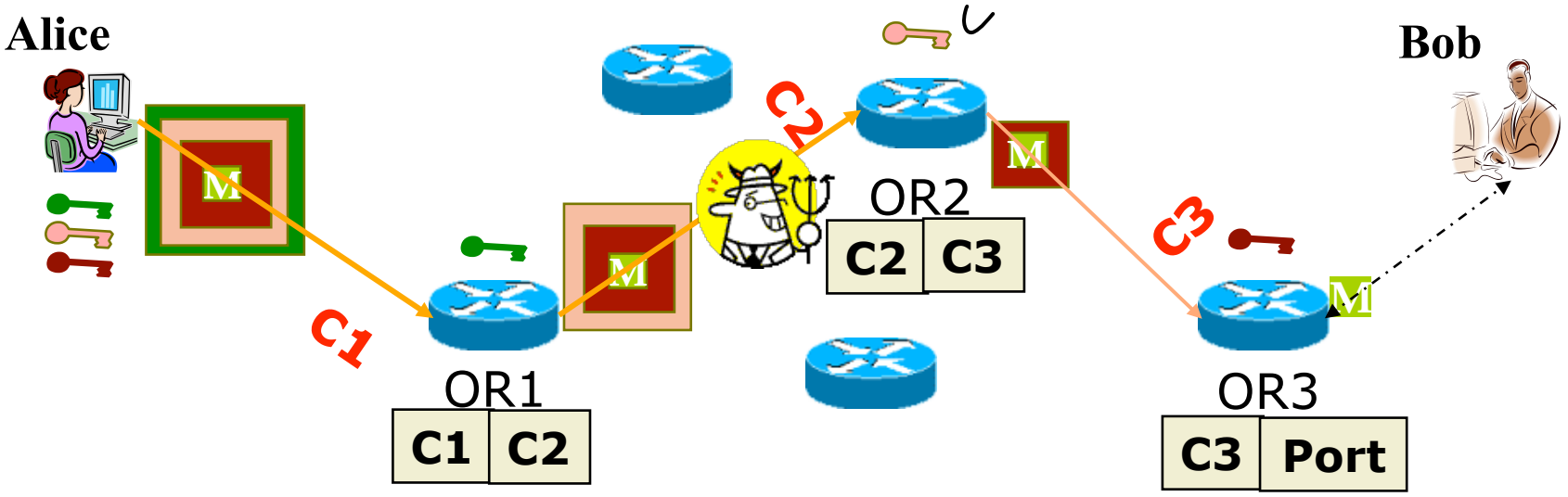
- **Client**: the user of the Tor network
- **Server**: the target TCP applications such as web servers
- **Tor (onion) router**: the special proxy relays the application data
- **Directory server**: servers holding Tor router information

How Tor Works? --- Circuits

- Alice herself chooses the relay routers and creates circuits through the relay routers
  - Circuit --- communication tunnel from Alice to Bob
  - These circuits are dedicated for Alice
- Can the routers along the circuit or a third party find communication relationship by checking the packet header?



How Tor Works? --- Onion Routing



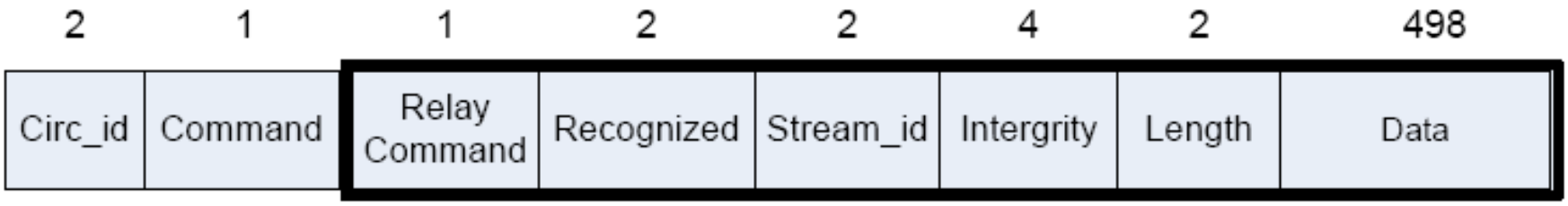
- A circuit is built incrementally one hop by one hop
- Onion-like encryption
  - Alice negotiates an AES key with each router
  - Messages are divided into equal sized cells
  - Each router knows only its predecessor and successor
  - Only the Exit router (OR3) can see the message, however it does not know where the message is from

Detailed Circuit Setup Steps: One-Hop Circuit

Alice (OP) | **Entry OR (OR1)** | **Middle OR (OR2)** | **Exit OR (OR3)** | **Bob**

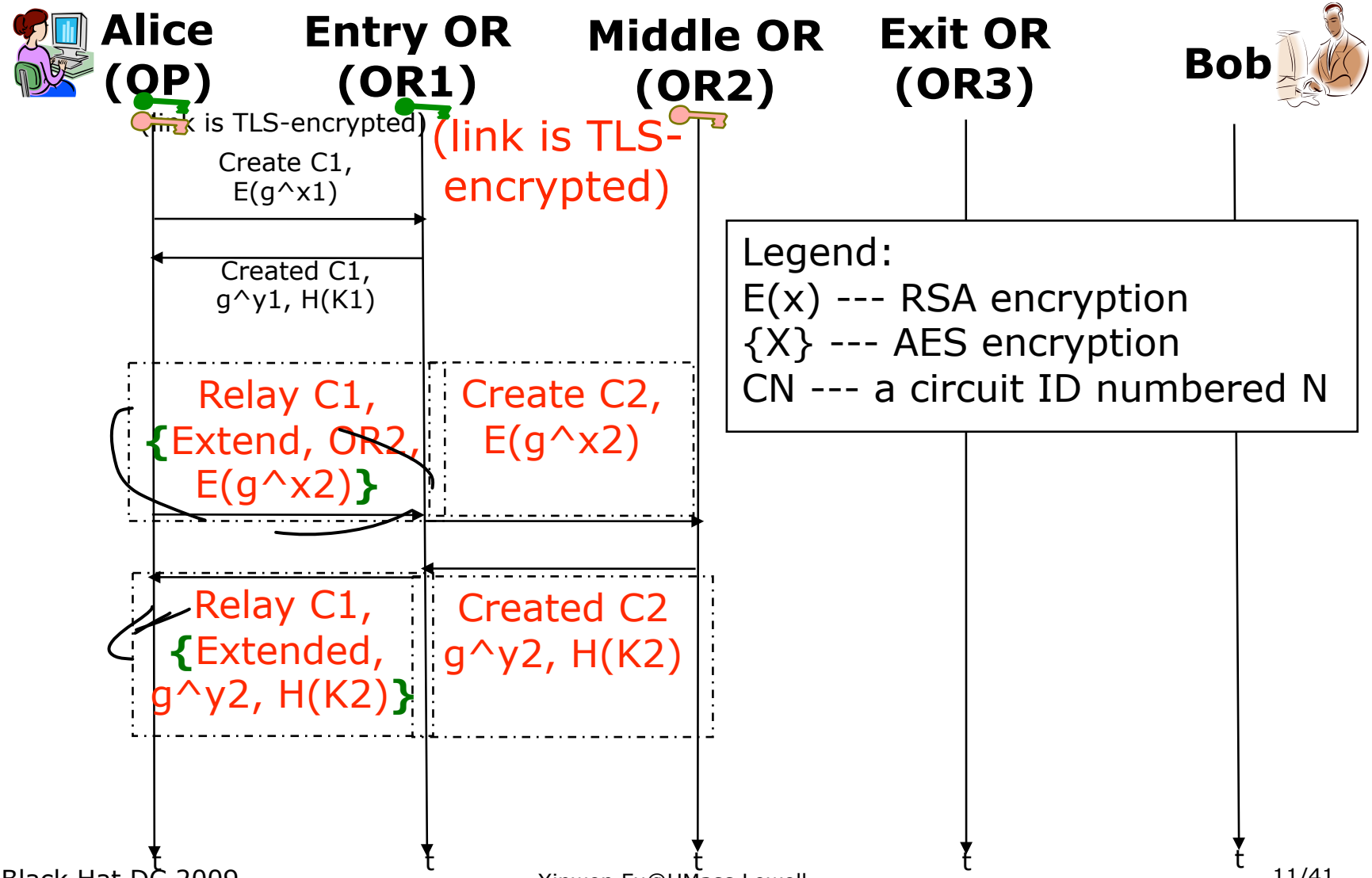
(link is TLS-encrypted)

(a) Tor Cell Format

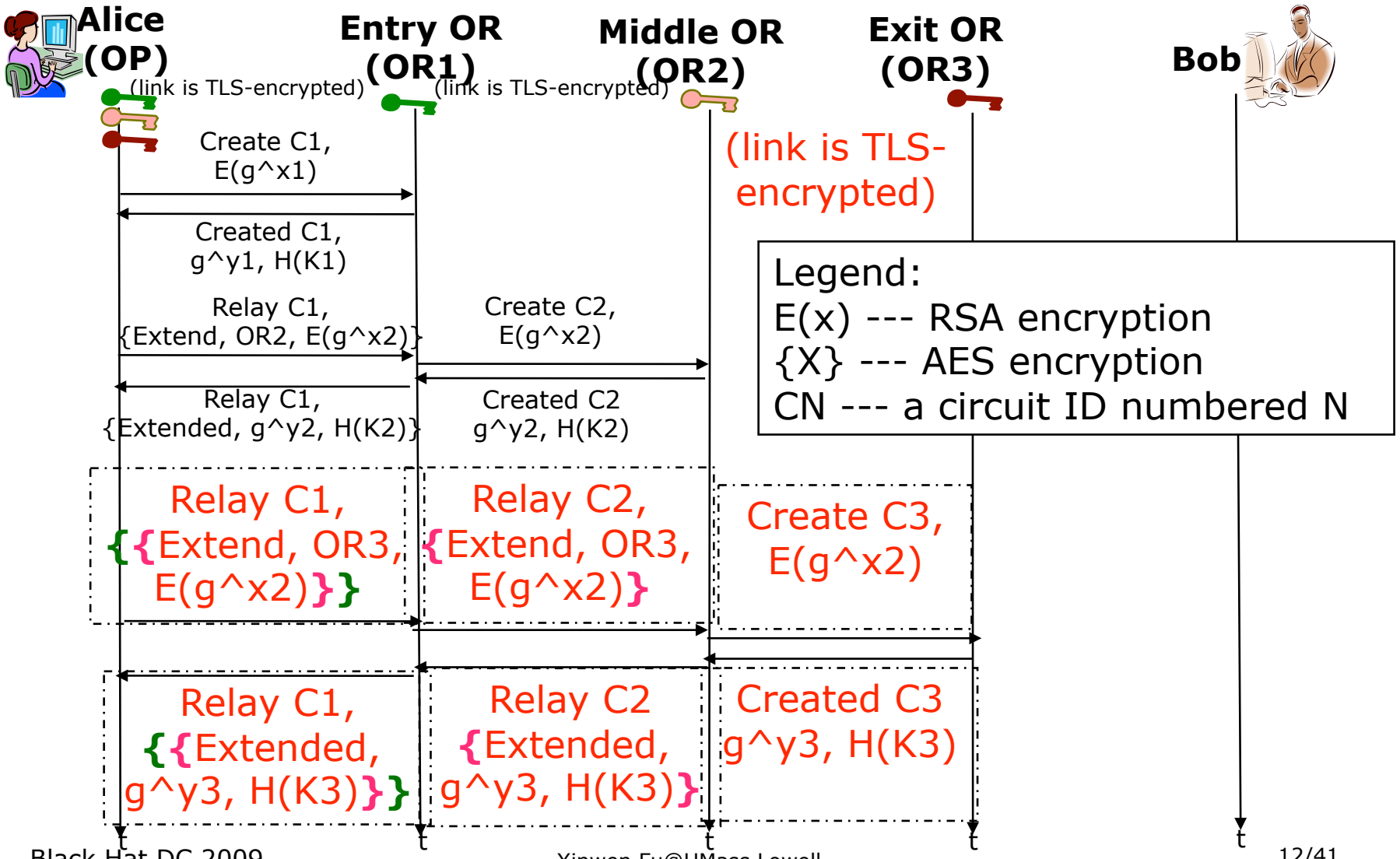


(b) Tor Realy Cell Format

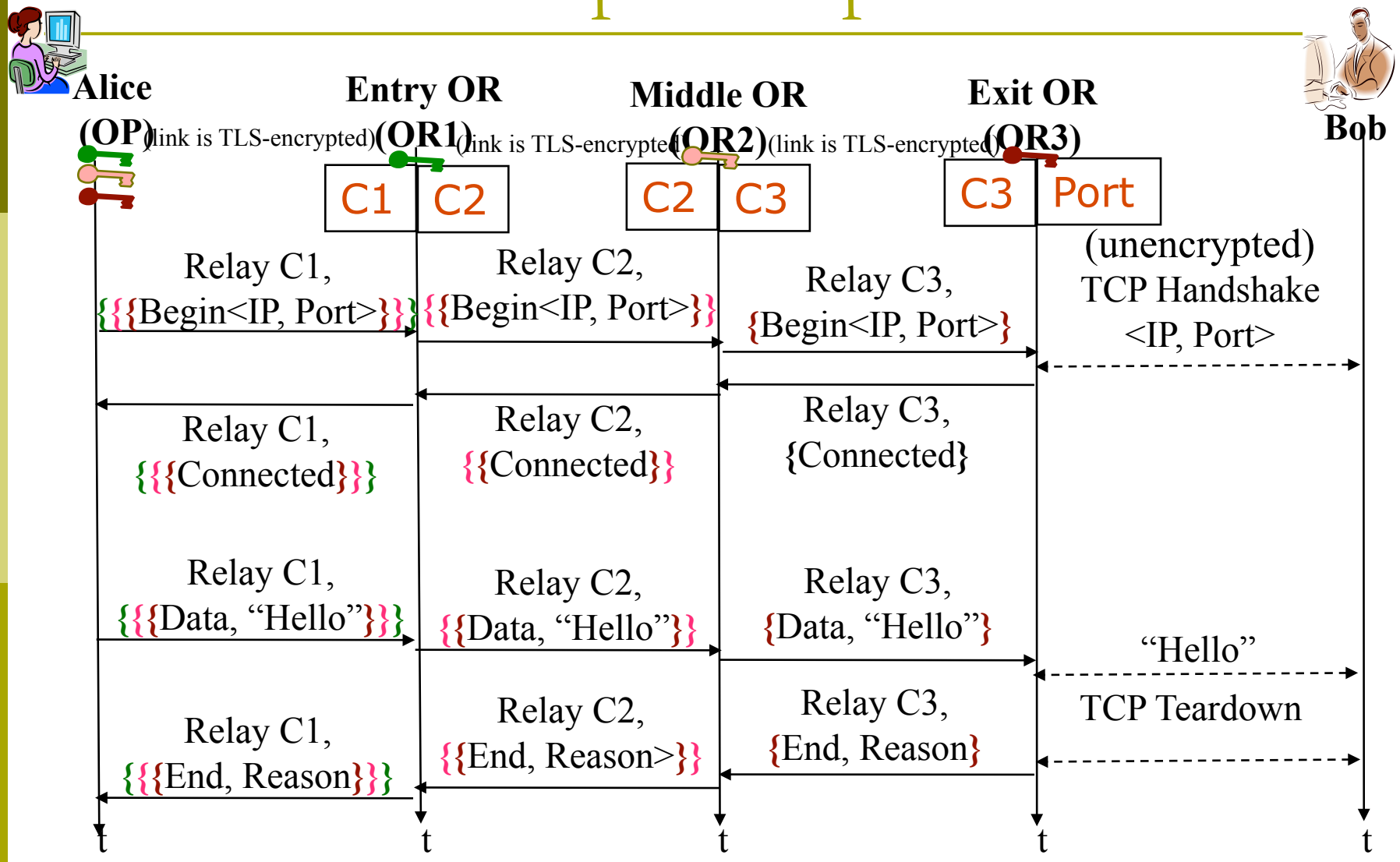
Two-Hop Circuit



Three-Hop Circuit



Connection Setup Example



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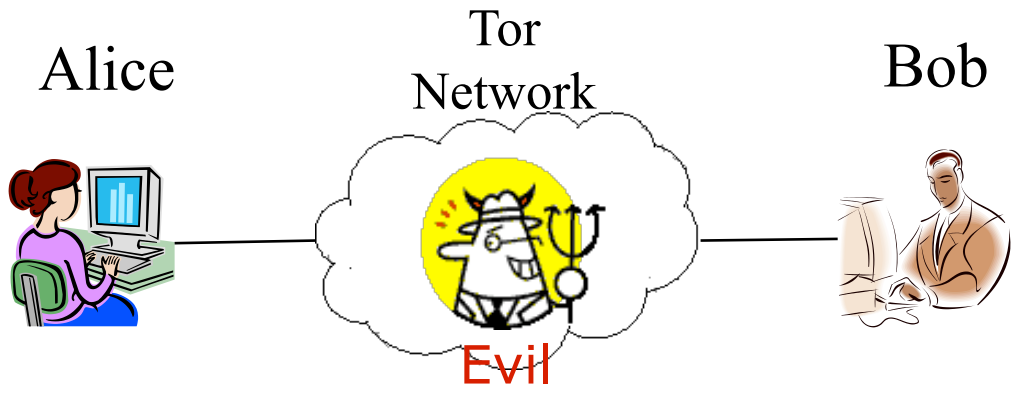
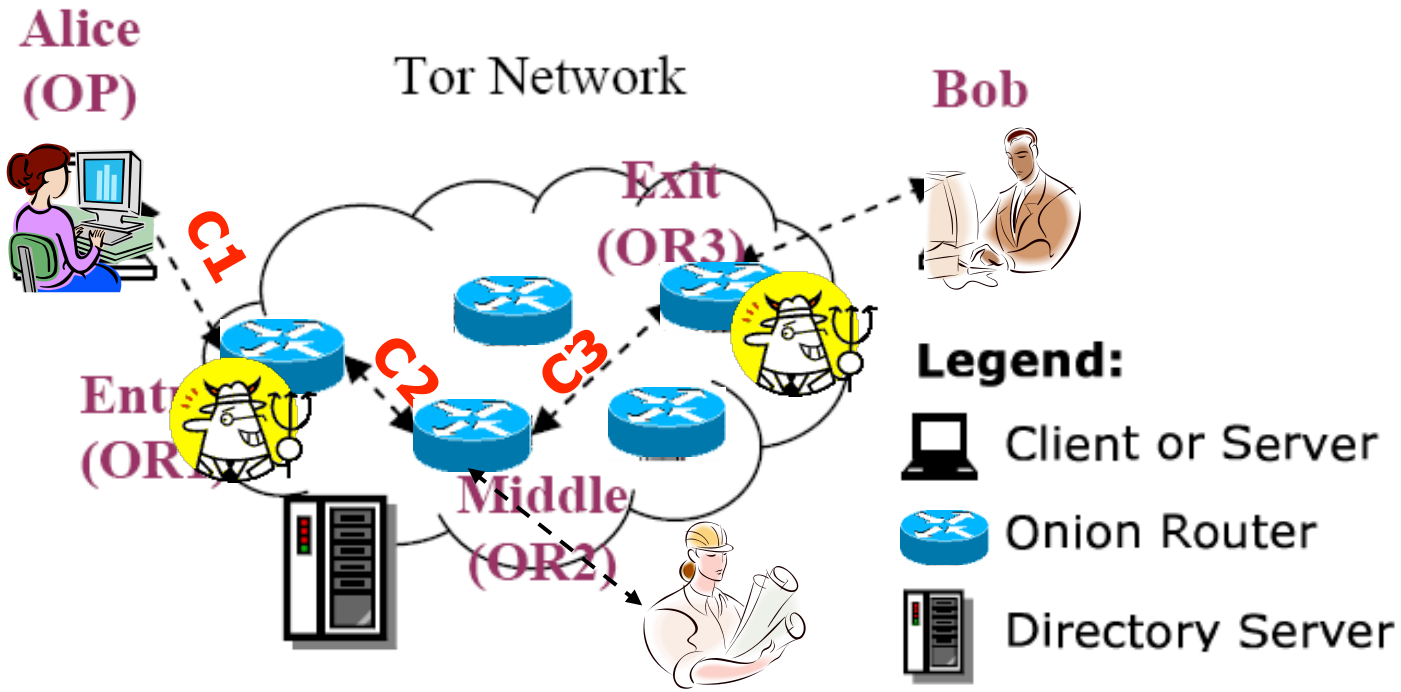
Problem Definition of Attacks against Tor



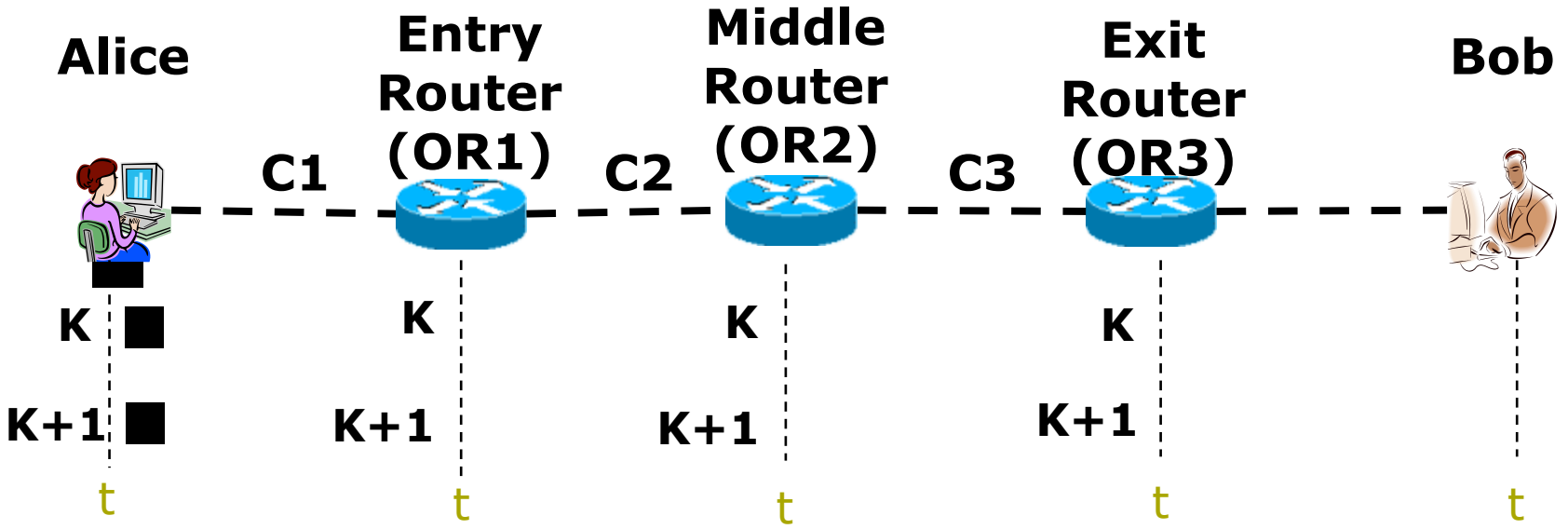
- Alice is sending messages to Bob through an encrypted and anonymous circuit, how can Evil confirm the communication relationship between Alice and Bob?

Attack Methodology



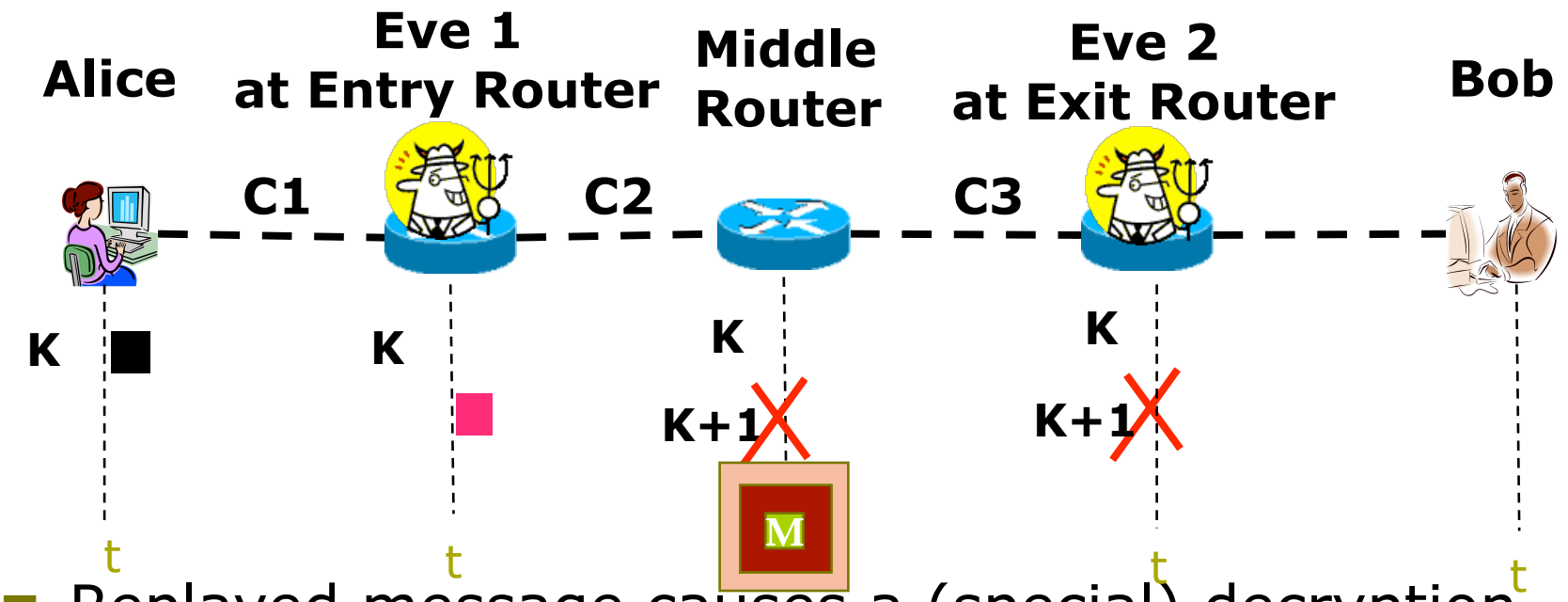
- If the attacker can determine circuit segments C1 and C3 belong to the same circuit, the attacker confirms the communication relationship for sure
  - Entry knows where the packet comes from and Exit knows where the packet goes

AES Counter – Normal Case



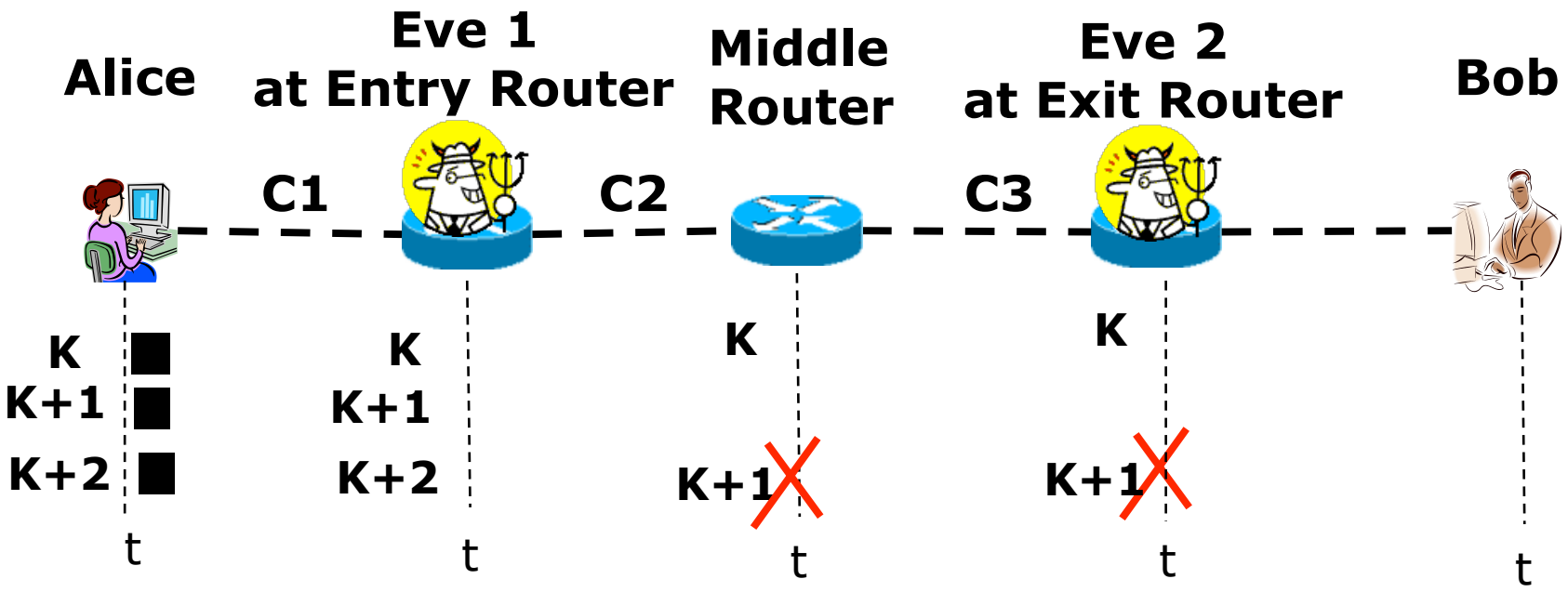
- A message comes from Alice through Circuit Segment C1, and goes to Bob after Circuit Segment C3
- An AES counter is synchronized through the circuit

AES Counter – Replay Attack Case



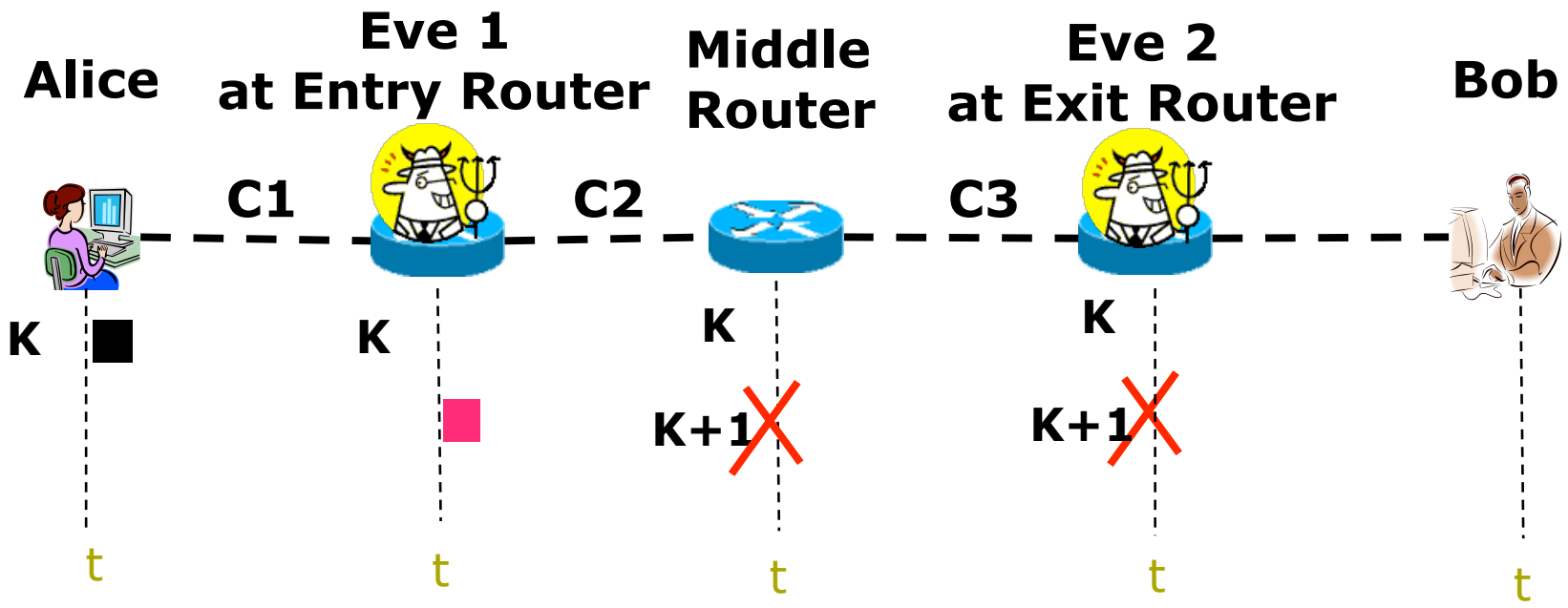
- Replayed message causes a (special) decryption error at the end of circuit C3 at Eve 2
  - The duplicated message disrupts the counter
- Therefore, Circuits C1 and C3 are created by Alice
- Claim: Alice is communicating with Bob

AES Counter – Deletion Attack Case



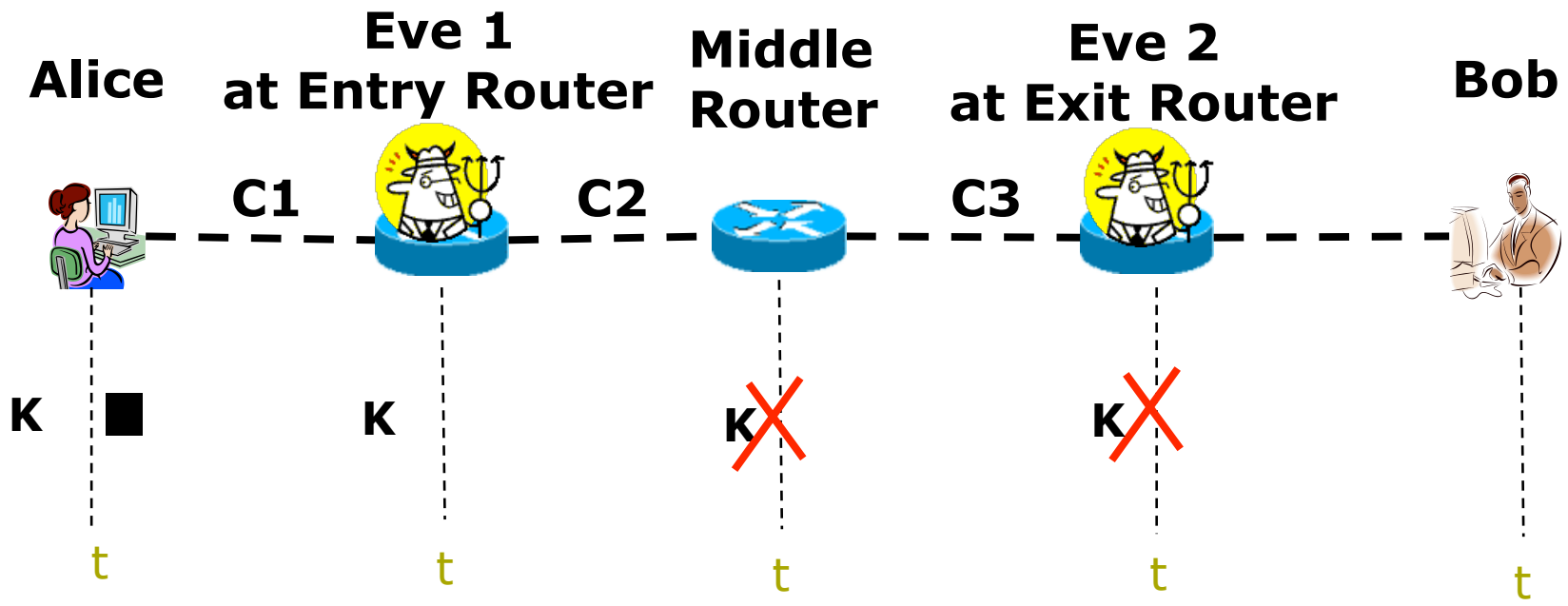
- The cell after the deleted cell causes decryption error

AES Counter – Insert Attack Case



- The inserted cell causes decryption error

AES Counter – Modify Attack Case

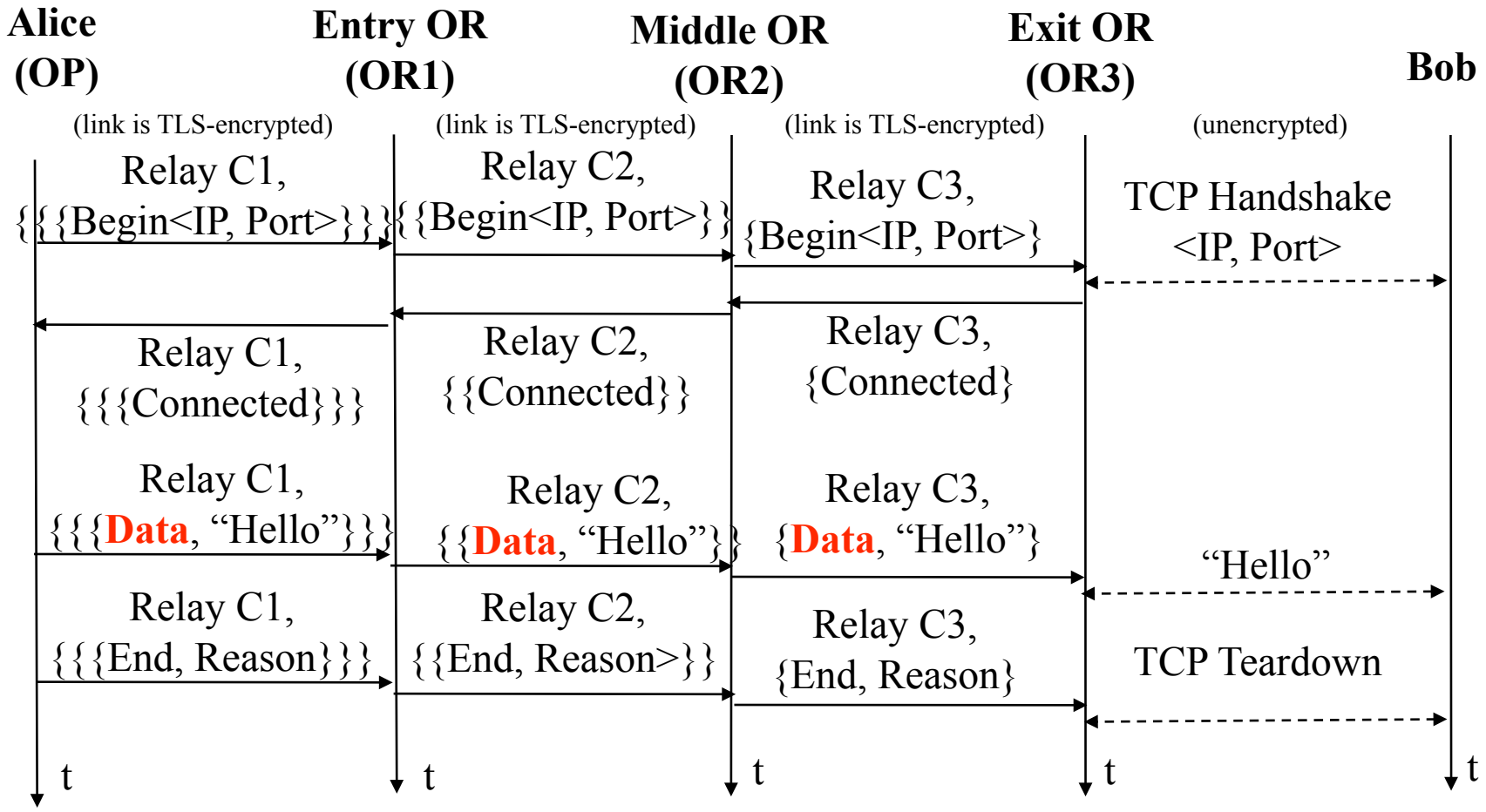


- The modified cell causes decryption error

Issues in Attacks Above

- Which cells and when to manipulate
  - The circuit is torn down when there is decryption error
- How to make attack stealthy
  - Broken circuits may render Alice's attention

Which Cells and When to Manipulate

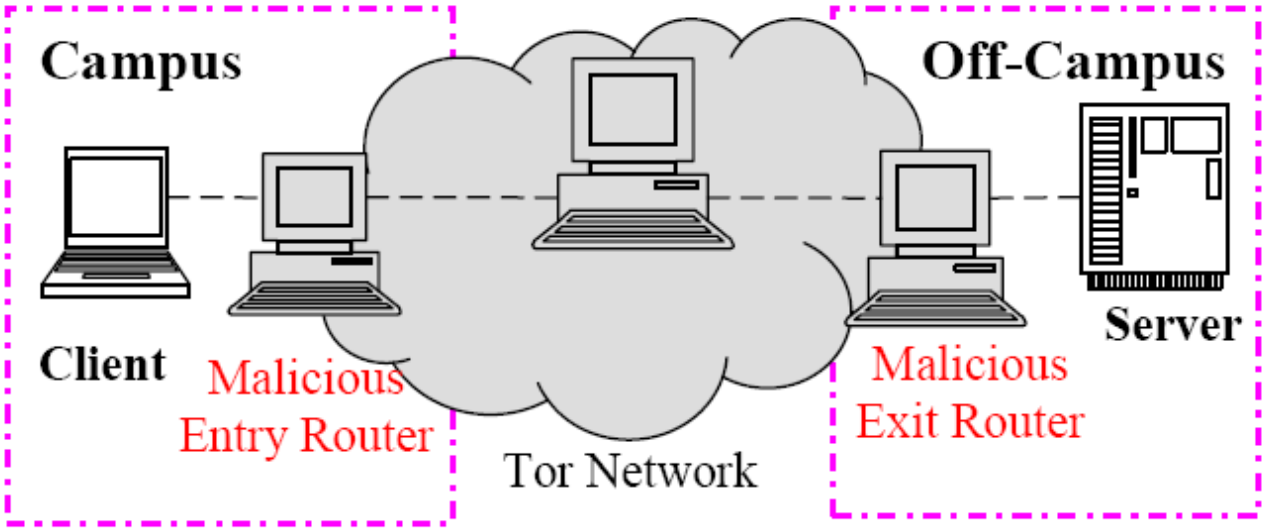


- Target data cells after the circuit is built
- Identify protocol status by counting cells

How to Make Attack Stealthy

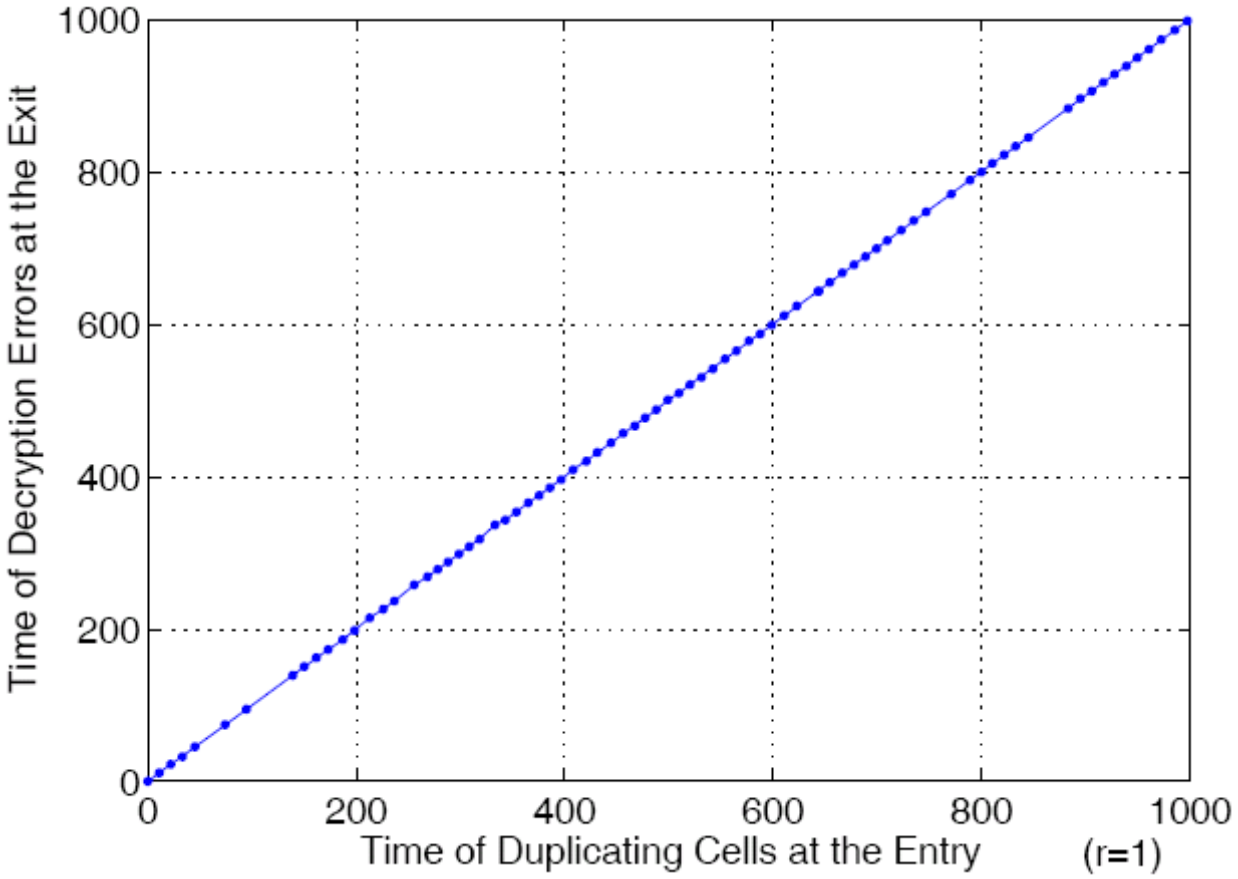
- Insert and replay attacks are very flexible and can be made stealthy can be applied freely
- When there is no traffic and a circuit is idle (the circuit already carried target traffic)
- At the end of the lifetime of a circuit
  - Default lifetime is 10 minutes
  - Before teardown
  - While holding teardown commands

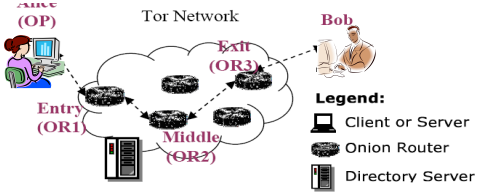
Experiment Setup



- One computer was setup as an exit router
- It takes two days for our second computer to become an entry router

Decryption Error Time v.s. Duplication Time





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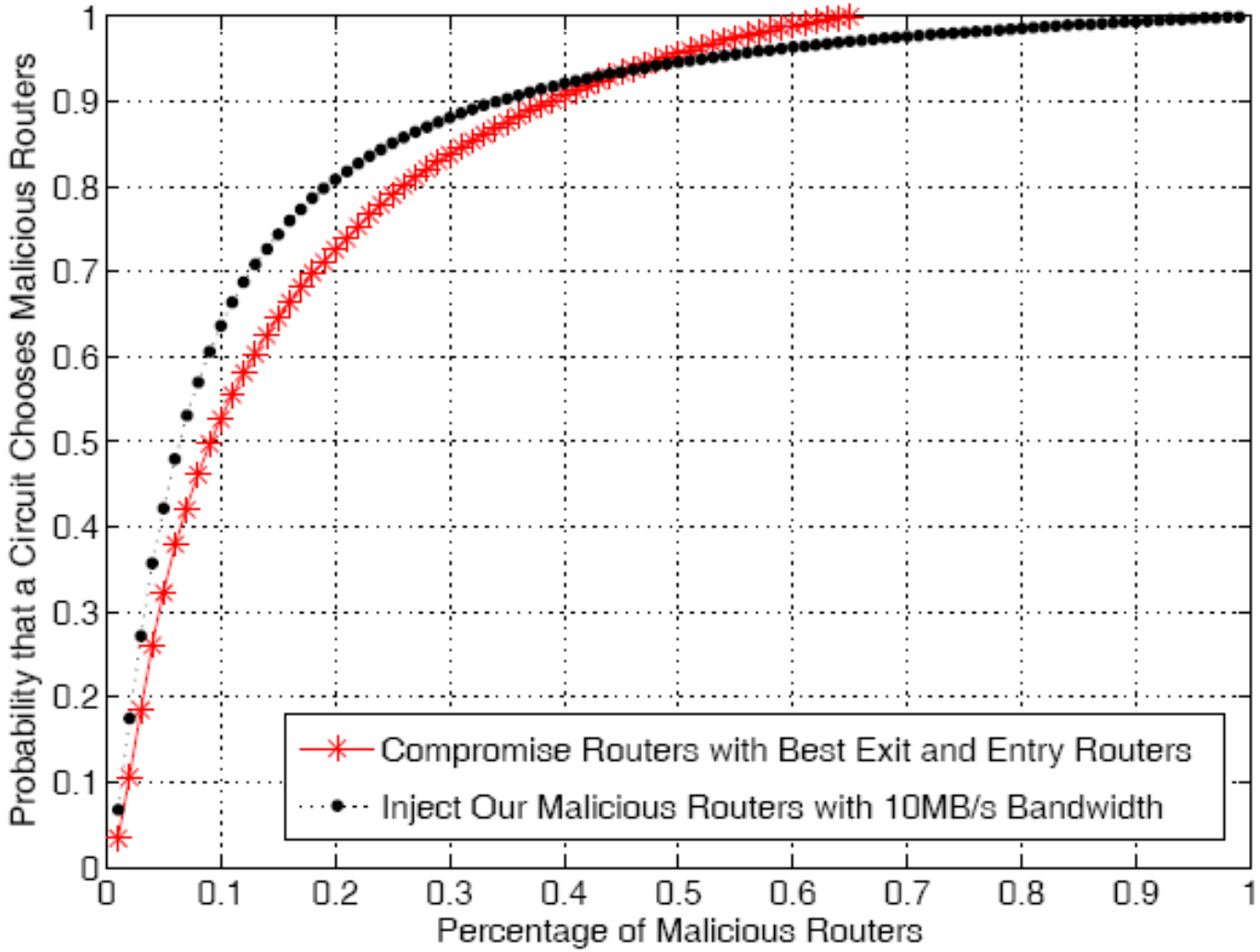
Impact

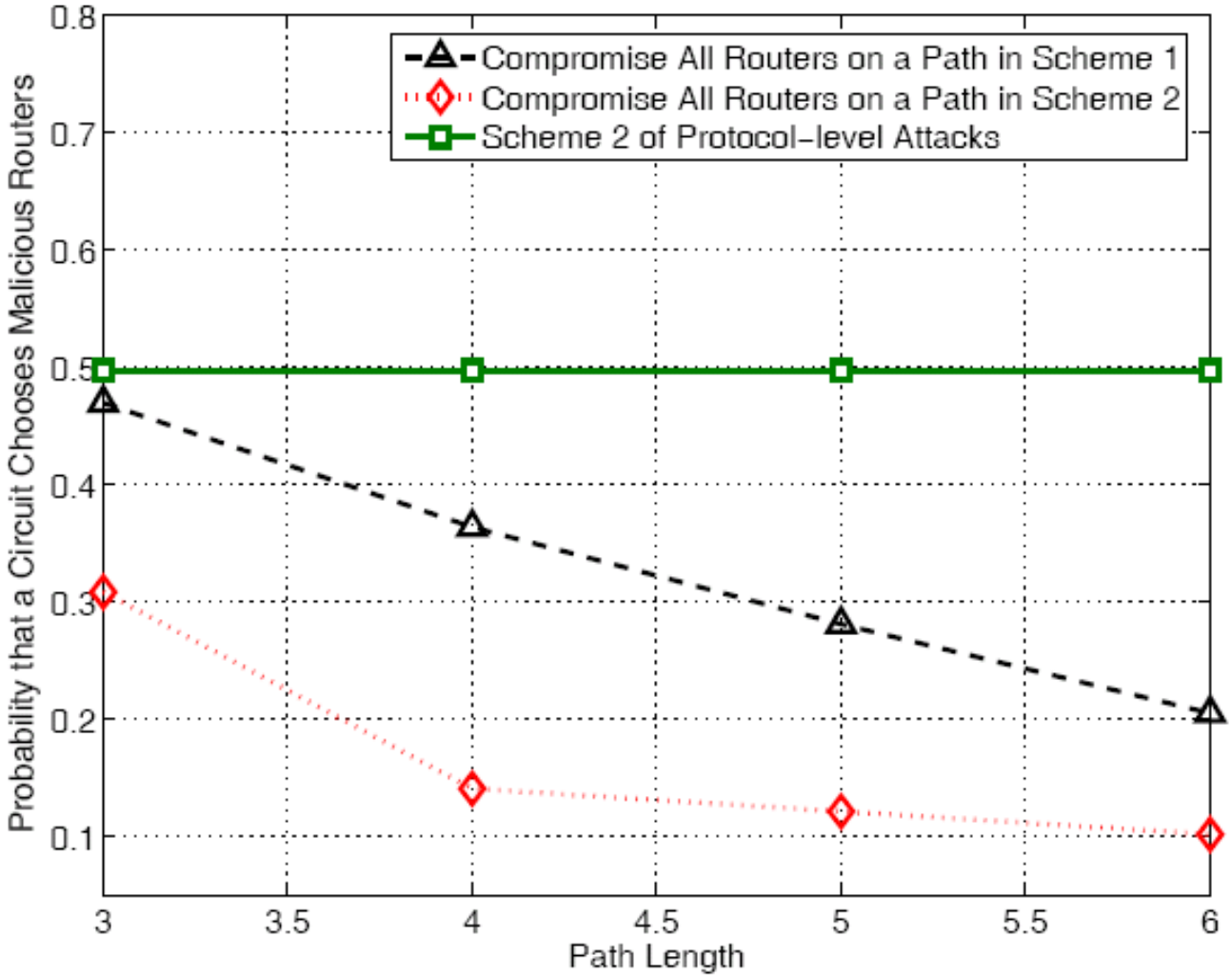
- Metrics: probability that a circuit chooses malicious Tor routers
  - A circuit chooses a malicious entry and exit, it is done
- Attackers can do the following in order to increase the probability
  - Scheme 1: Inject (donate) high-bandwidth routers into the Tor network
  - Scheme 2: Compromise high-bandwidth Tor routers into the Tor network

Big Impact: 9% v.s. 60%



Protocol-level Attack v.s. Brute Force Attack

- Brute force attack: attackers occupy all routers on a circuit



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Hard to Defend

- No easy way to defend against replay, insert, delete and modify attacks because of the anonymity maintained here
  - The attacks are flexible can be deployed at any moment during the life time of a connection
  - What if attackers just attack for DoS?
- Careful routing protocols
  - Choose routers in different countries or regions in order to prevent a single organization from deploying the attack

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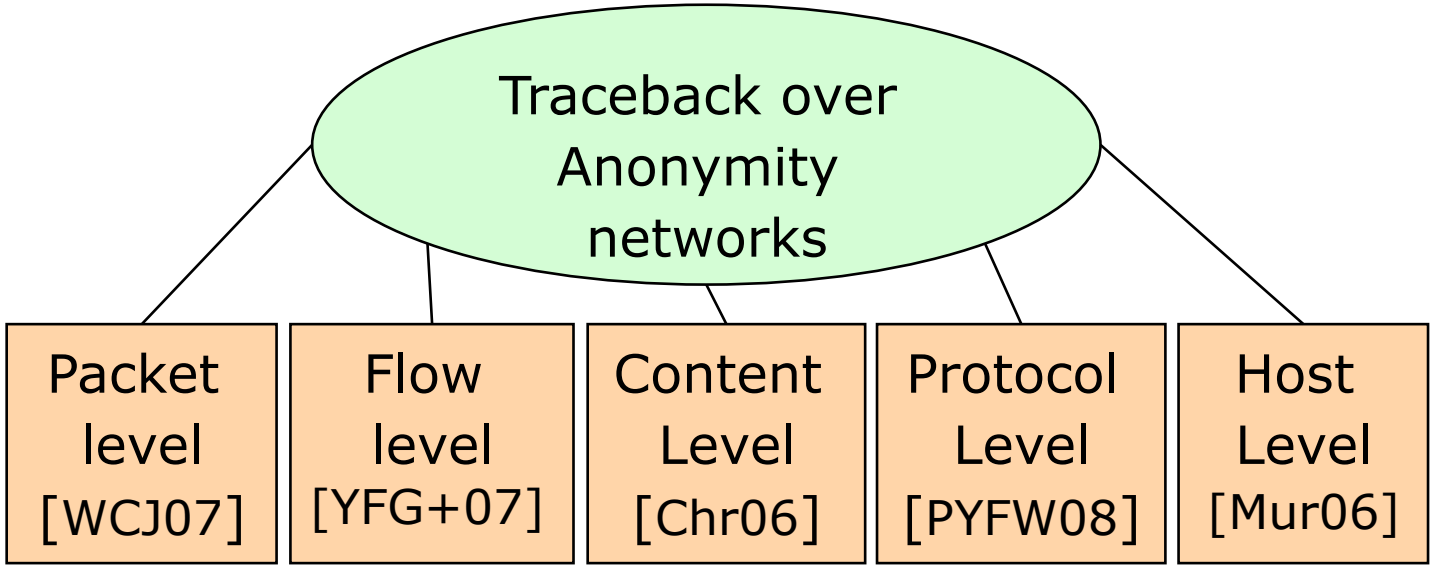
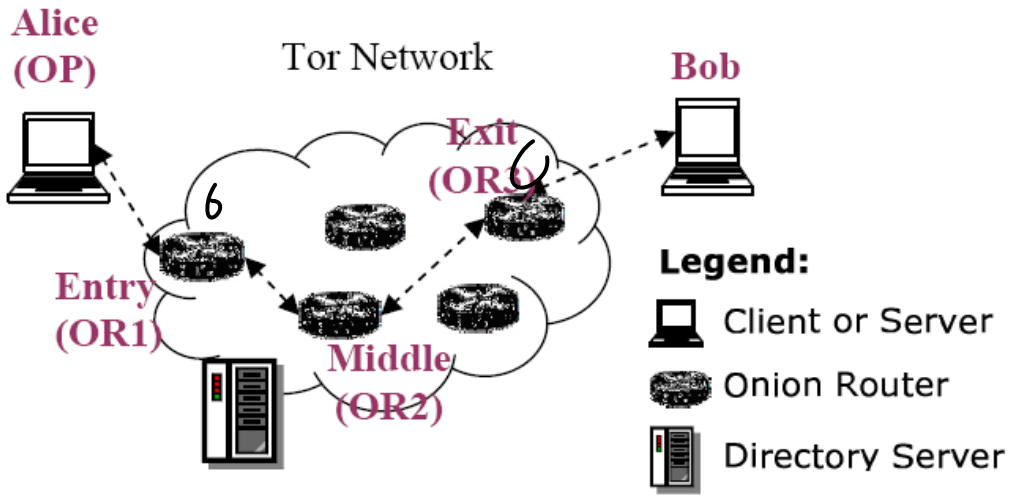
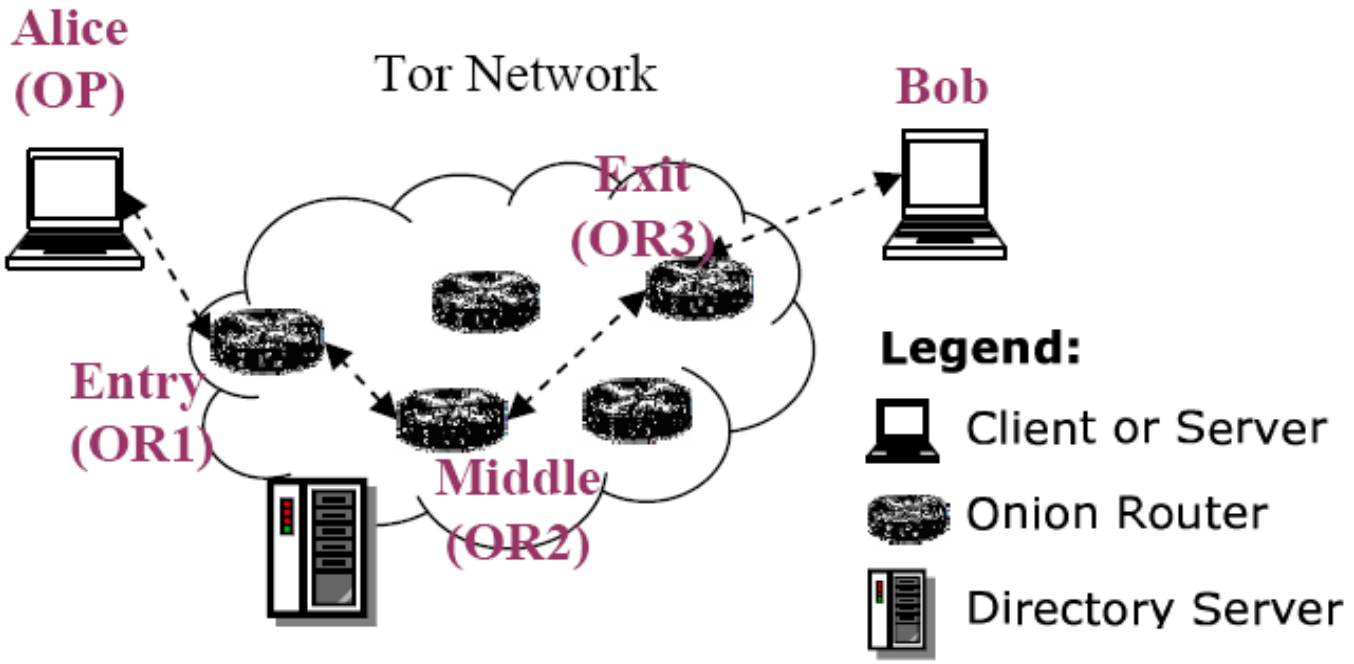
Many Attacks





Tagging Attacks

- Outside attackers mark attacks: use TLS to guarantee integrity
- Protocol-level attacks are by inside attackers



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Summary

- We identified a class of new attack, protocol-level attack, against anonymous communication network Tor
  - Need only one cell to confirm the communication relationship
  - One attack can confirm multiple connections using the same circuit
  - Confirmation is a sure thing (100%)
- Our experiments validate the feasibility and effectiveness of all attacks
- The impact is huge
  - Given 9% percent of Tor routers are malicious, over 60% of the connections can be compromised

Future Work

- Develop countermeasure against the protocol-level attack
  - Tor is a pioneer software for on-line privacy
- Fight the abuse of Tor (forensic traceback)
  - Anonymous networks may be abused
  - Government has resource and donates high-performance routers and bandwidth to Tor in exchange of necessary surveillance
  - The abuse of Tor threatens Tor

Acknowledgment

- Tor developers
- Other Tor researchers

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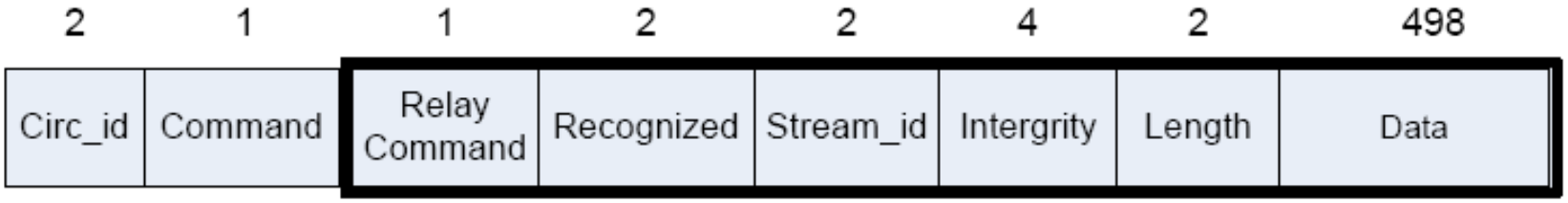
Thank you!

Xinwen Fu

Cell Format in Tor

(a) Tor Cell Format



(b) Tor Realy Cell Format