Security in Wireless Broadcast

Never Stand Still

COMP4337/9337

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Outline

- Quick overview of Elliptic Curve Deffie-Hellman (ECDH) and Datagram TLS as lightweight solution for many wireless (IoT) solutions.
- Security Challenges in wireless broadcast
- Advanced techniques using hash-chains, Merkle Tree
- Application case study of Code dissemination in a multi-hop wireless network

Datagram TLS (DTLS)

- SSL Designed to run on top of TCP
- Datagram TLS developed later to run over connectionless UDP
  - RFC 4347 for details
- Already supported by several implementations
- Very similar to TLS
  - Needs extra control messages as UDP doesn't provide these like TCP
  - Sequence number in record header to protect from Replay attack
- If very lossy network, may have issues with lot of restranmissons for reliability

Elliptic Curve (ECC) Scheme

- Key Agreement, aka, Elliptic Curve Deffie-Hellman (ECDH)
  - Allows for establishment of shared secret similar to DH
  - The shared key is then used for symmetric encryption or for further session/temporal key derivation
- Digital Signature: Elliptic Curve Digital Signature Algorithm (ECDSA), allows use of public/private key for signing a message and verification of signature, more efficient than RSA based DSA.

Elliptic Curve Cryptography

- Elliptic curve cryptography (ECC) is an approach to public-key cryptography based on the algebraic structure of elliptic curves over finite field.
- ECC presents various benefits over RSA such as:
  - fast computation
  - small key size
  - compact signatures.
- For example, to provide equivalent security to 1024-bit RSA, an ECC scheme only needs 160 bits.

Elliptic Curve Diffie-Hellman Key Exchange

1. Alice and Bob publicly agree on an elliptic curve E over a finite field Z_p.
2. Next Alice and Bob choose a public *base point* B on the elliptic curve E.
3. Alice chooses a random integer $1<\alpha<|E|$, computes P $= \alpha$ B, and sends P to Bob. *Alice keeps her choice of α secret.*
4. Bob chooses a random integer $1<\beta<|E|$, computes Q $= \beta$ B, and sends Q to Alice. *Bob keeps his choice of β secret.*

1. Alice and Bob choose E to be the curve $y^2 = x^3+x+6$.
2. Alice and Bob choose the public base point to be B=(2,4).
3. Alice chooses $\alpha = 4$, computes $P = \alpha B = 4(2,4) = (6,2)$, and sends P to Bob. *Alice keeps α secret.*
4. Bob chooses $\beta = 5$, computes $Q = \beta B = 5(2,4) = (1,6)$, and sends Q to Alice. *Bob keeps β secret.*

ECDH Key Exchange (cont.)

5. Alice computes $K_A = \alpha Q = \alpha(\beta B)$.
6. Bob computes $K_B = \beta P = \beta(\alpha B)$.
7. The shared secret key is $K = K_A = K_B$.

- Even if Eve knows the base point B, or P or Q, she will not be able to figure out α or β, so K remains secret!

5. Alice computes $K_A = \alpha Q = 4(1,6) = (4,2)$.
6. Bob computes $K_B = \beta P = 5(6,2) = (4,2)$.
7. The shared secret key is $K = (4,2)$.

Recap: How to use keys?

- Rule of thumb:
- Public Key Cryptography: slow
- Symmetric Cryptography: fast

- Hence, do not encrypt large messages with Public Key Cryptography
- Encrypt a random, fresh symmetric key with Public Key Cryptography
- Use this key and symmetric encryption to encrypt a large message

- For signature, only sign the hash value of messages

- Send the encrypted key, signature, and symmetrically encrypted message to your communication partner

Challenges for Broadcast Security

- Broadcast applications need security
  - Packet injection or eavesdropping is easy
- Security solutions for point-to-point communication not suitable secure for broadcast
- Broadcast challenges
  - Scale to large audiences
  - Dynamic membership
  - Low overhead (computation & communication)
  - Packet loss
    - How to achieve reliability in broadcasts?

Scale & Dynamics

- Small groups contain up to ~100 members
- Medium-size groups contain 100-1000 members
- Large groups contain 1000-10^9 members – e.g. IoT
- How does scale affect security?
- Dynamic membership: members may join and leave at any time
- How do dynamics affect security?

Communication Pattern

- Group can be single-source broadcast
  - One-to-many
  - SSM: Single-source multicast, source-specific multicast
- Multiple-source broadcast
  - Some-to-many
- All members broadcast
  - Many-to-many

Reliable Broadcast Transmission

- How to reliably and scalably disseminate data to large numbers of receivers?
- Challenges
  - Ack implosion problem if receivers return Ack to sender for received packets
  - Nack implosion problem is severe as well
  - For large numbers of receivers, there usually is a fraction of them that do not obtain message
  - Local repair mechanisms (create tree topology and ask upstream parent for packet) faced numerous scalability difficulties
    - Accumulate ack (delayed) and send to parent node on the tree.

End-to-End approach ?

- Trusted server authenticates each node and distributes the key.
- Use well-known E2E protocols such as (D)TLS, IPSEC, SSL.

Pros

- Higher security level
- Dynamic grouping

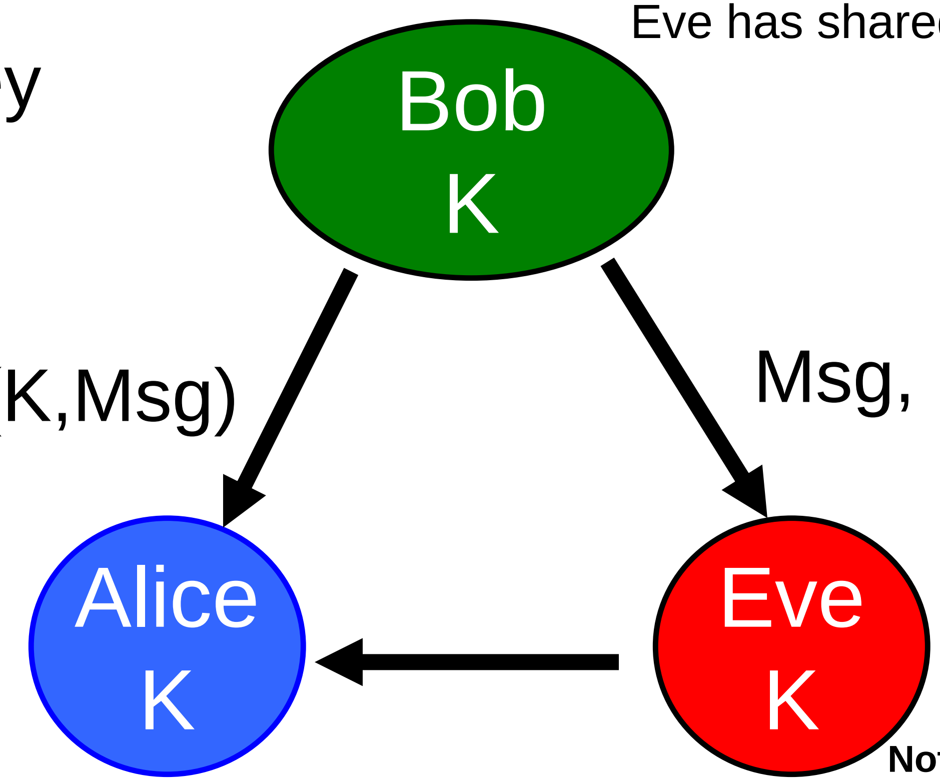
Cons

- Extremely higher ciphertext overhead due to one by one transfer
- Higher computation requirements

Shared Key: Easy to Forge

MAC: Message Authentication Code
Eve has shared Key

K = shared key



Msg, MAC(K,Msg)

Msg, MAC(K,Msg)

Note: Eve has legit shared Key - insider

Forged Msg, MAC(K, Forged Msg)

Asymmetric Key: Digital Signature

- Sign each packet and verify using Asymmetric key
- However, Signatures are expensive esp. for low end processors, e.g., RSA 2048:
  - High generation cost (~1 millisecond), High verification cost (~0.1 millisecond), High communication cost (256 bytes/packet)
- If we use one signature over multiple packets, intolerant to packet loss

Trivial broadcast key distribution

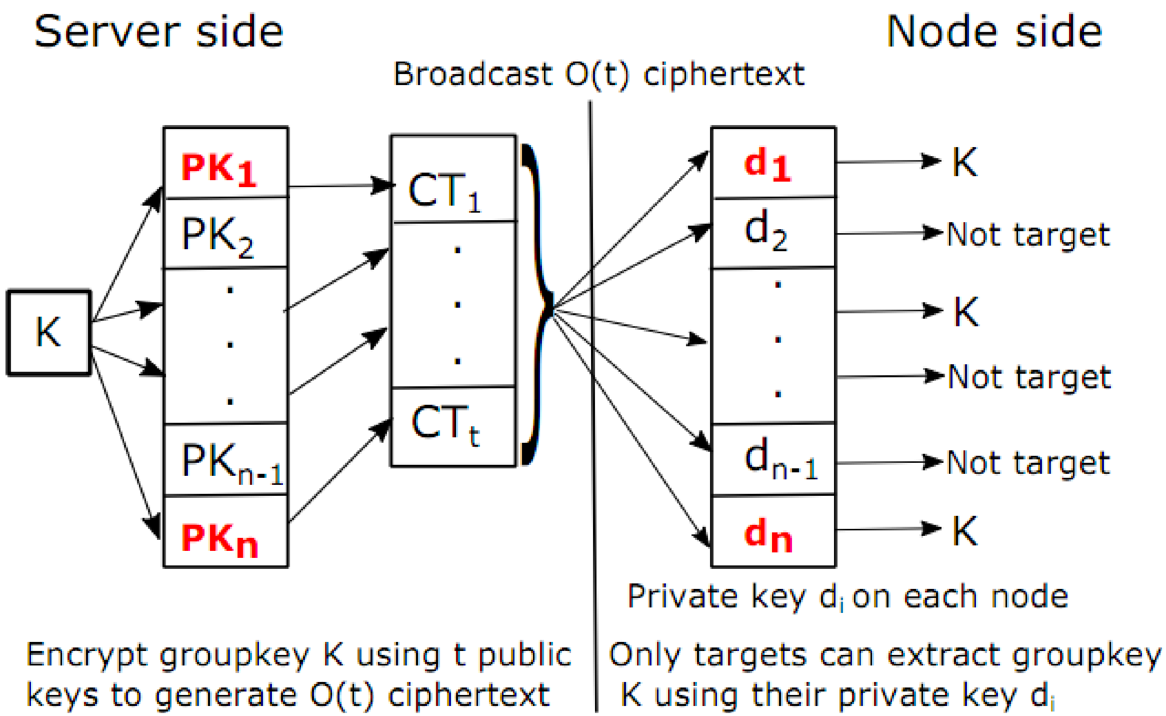


Figure 1: Trivial Broadcast Encryption scheme in an n nodes network targeting t nodes. K: shared group key. PK: Public Key. CT: Ciphertext. d: Decryption using each node's private key.

Trivial (2)

- Very simple and effective system. Easy to implement.
- The only issue is linear ciphertext O(t) for key distribution.
- Good for applications with smaller number of target nodes.
- Possible solution for non-sensor applications such as Desktop, smart-phone
- Optional reading: Stinson, Douglas R. *Cryptography: theory and practice*. CRC press, 2005.

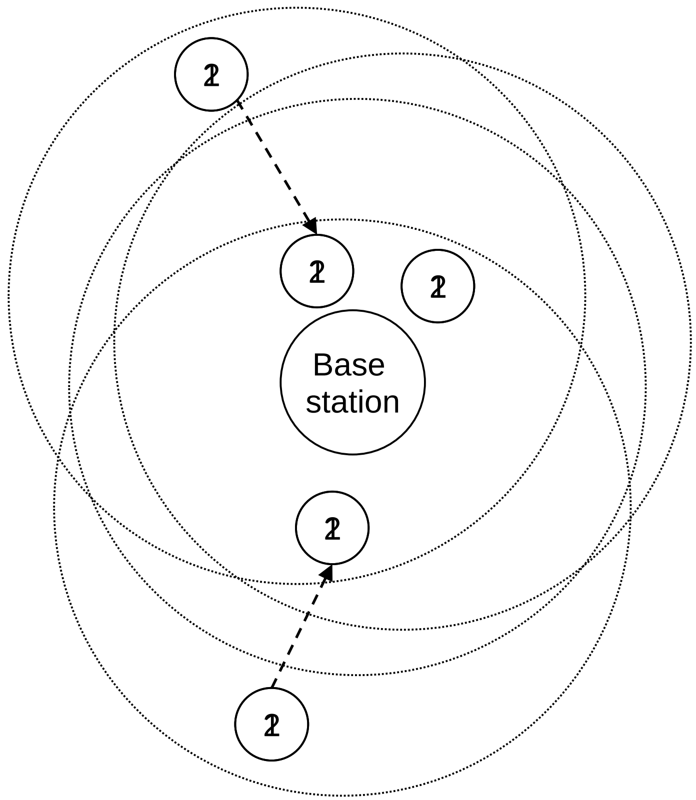
Broadcast Authentication Protocol

- *k* different keys to authenticate every message with *k* different MAC's
- Each receiver knows *m*-keys and hence verifies m MAC's.
- Key distribution in such a way that no coalition of *w* receivers can forge a packet for a specific receiver
- Assumptions on number of colluding receivers (on the order of *k*)
- Refer to (optional read, lot of work in crypto)R. Canetti, J. Garay, G. Itkis, D. Micciancio, M. Naor, and B. Pinkas. Multicast security: A taxonomy and some efficient constructions. In *INFOCOMM'99*, pages 708–716, March 1999.

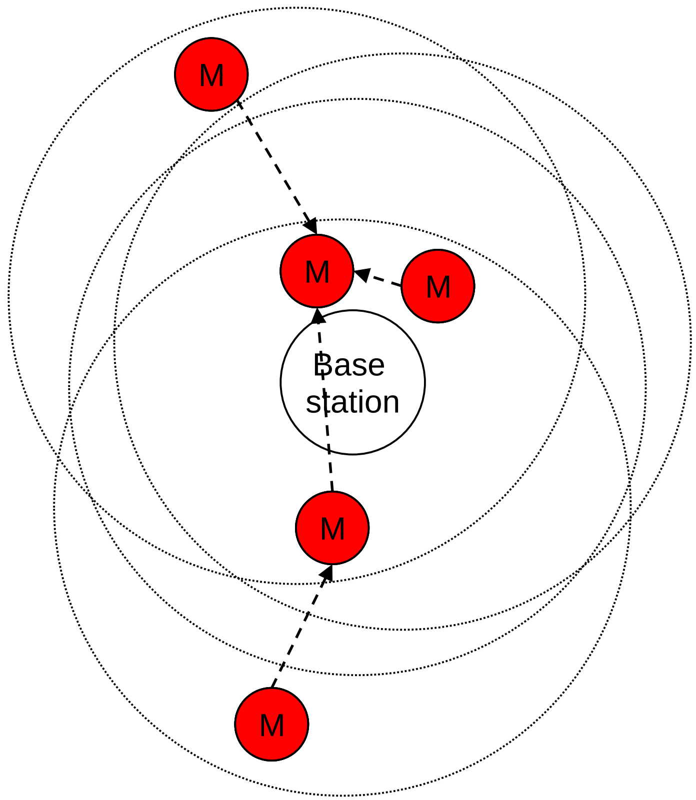
Hash Chain -basics

- Client generate 1000 hashes for password
  – Suggested by Lamport for password protection
- Server stores H^{1000}(password)
- Client willing to authenticate sends H^{999}(password)
- Server computes H^{1000}(password) = $H(H^{999}$(password))
  – Match found, store H^{999}(password)for next time
- Eavesdropper can't use H^{999}(password) since server expects H^{998}(password)

Case Study: Multi-hop code distribution

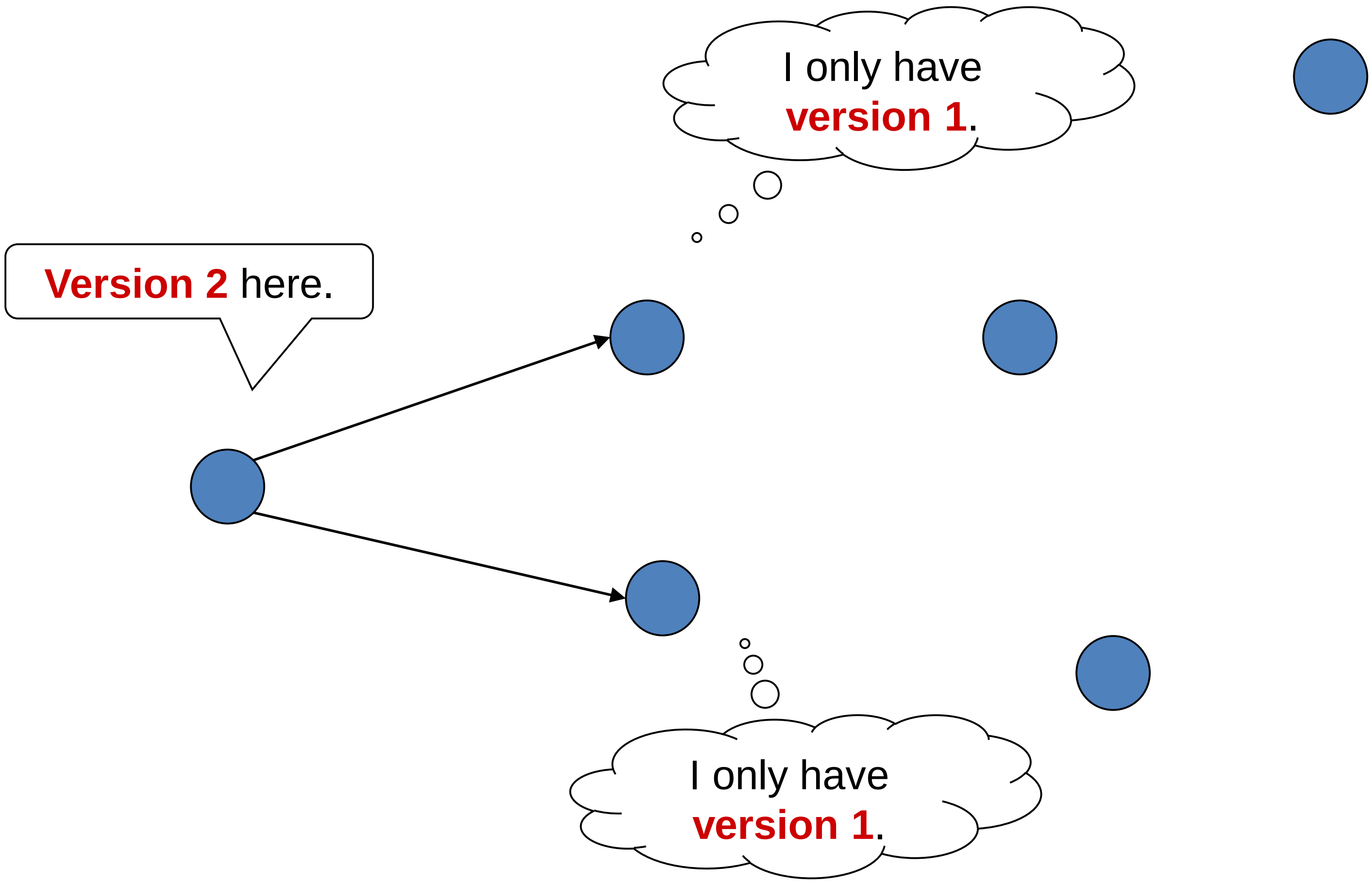


Attack by a compromised node



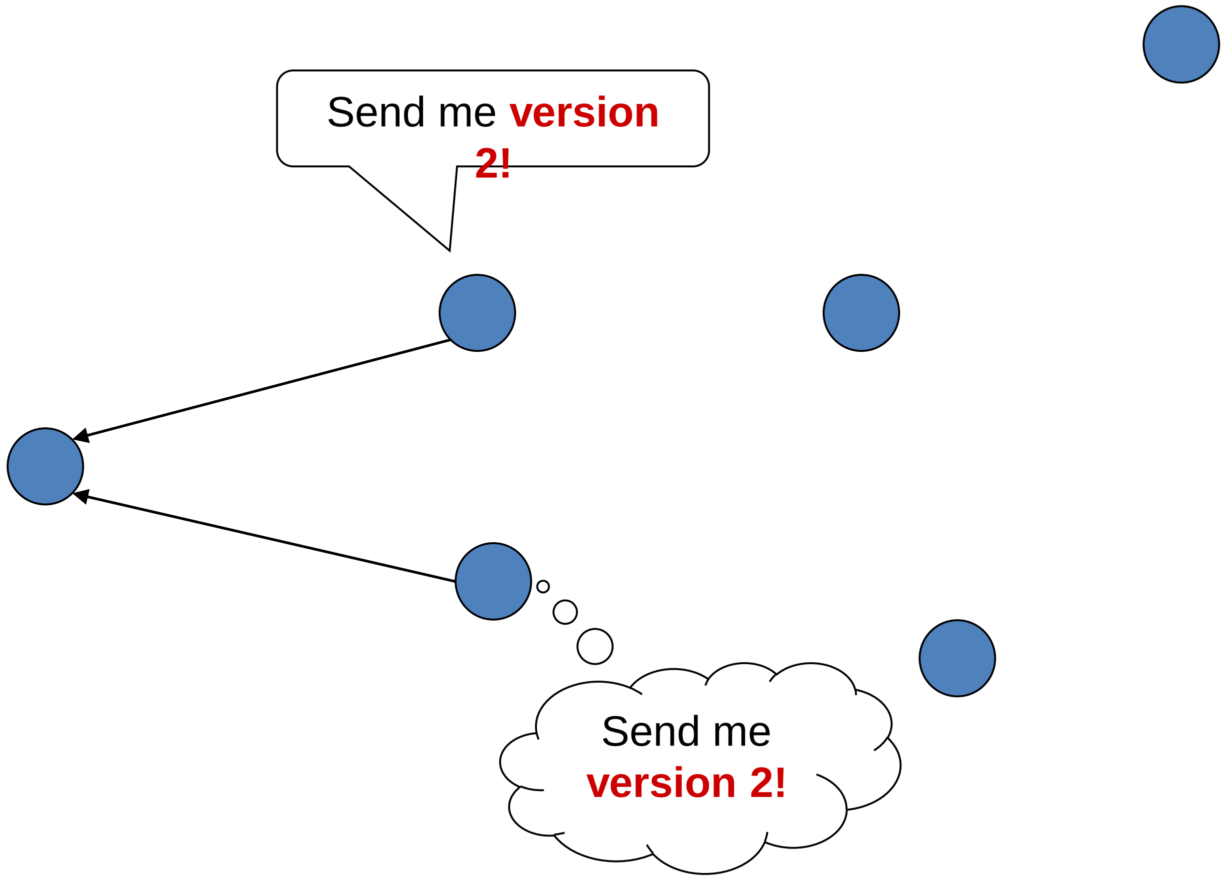
Epidemic propagation (1)

1. Nodes periodically advertise



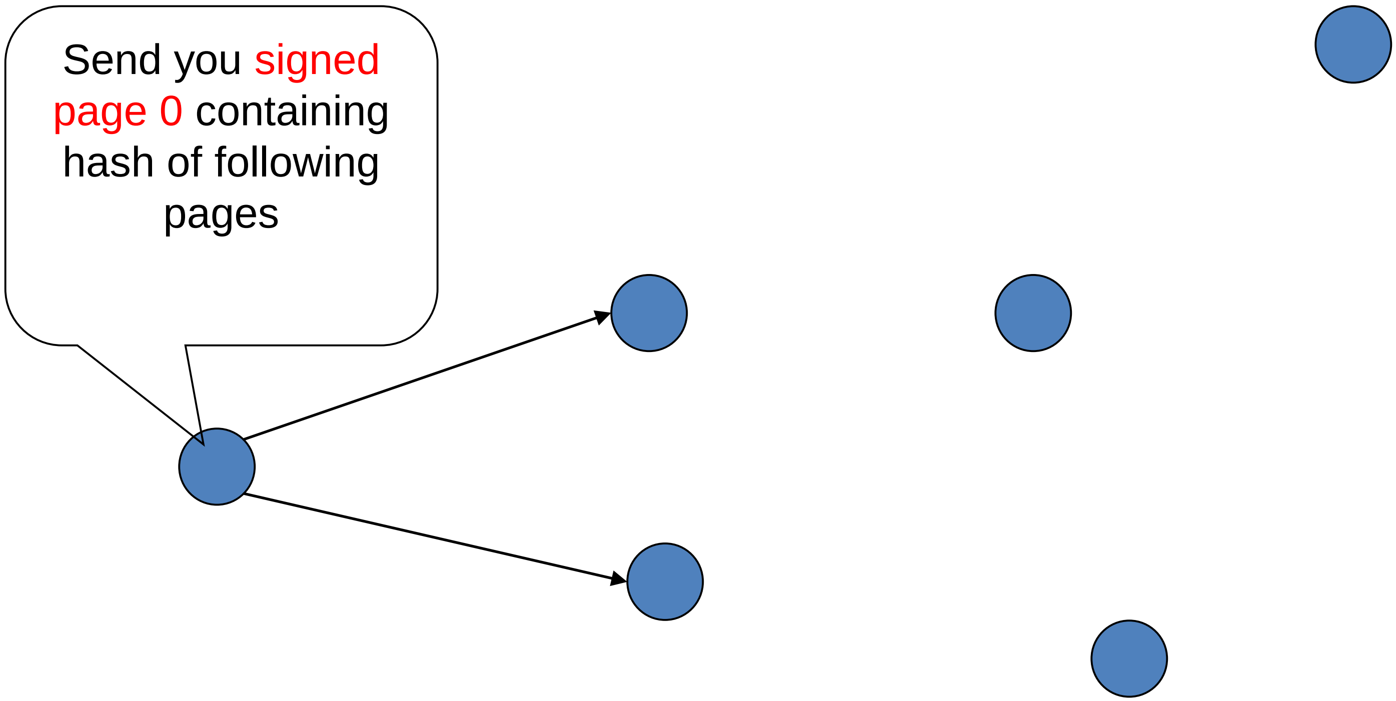
Epidemic propagation (2)

2. Neighboring nodes request new version



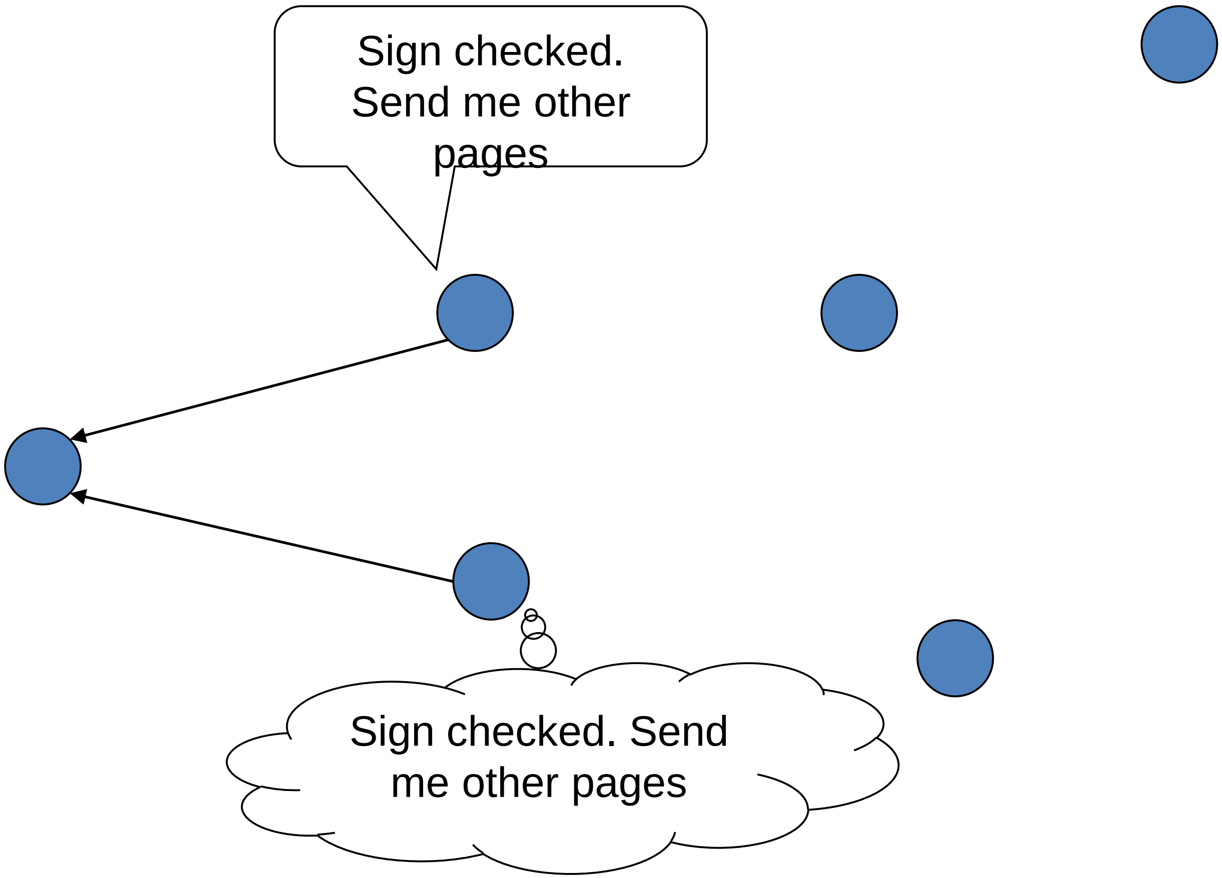
Epidemic propagation(3)

3. Server sends signed hash of each page



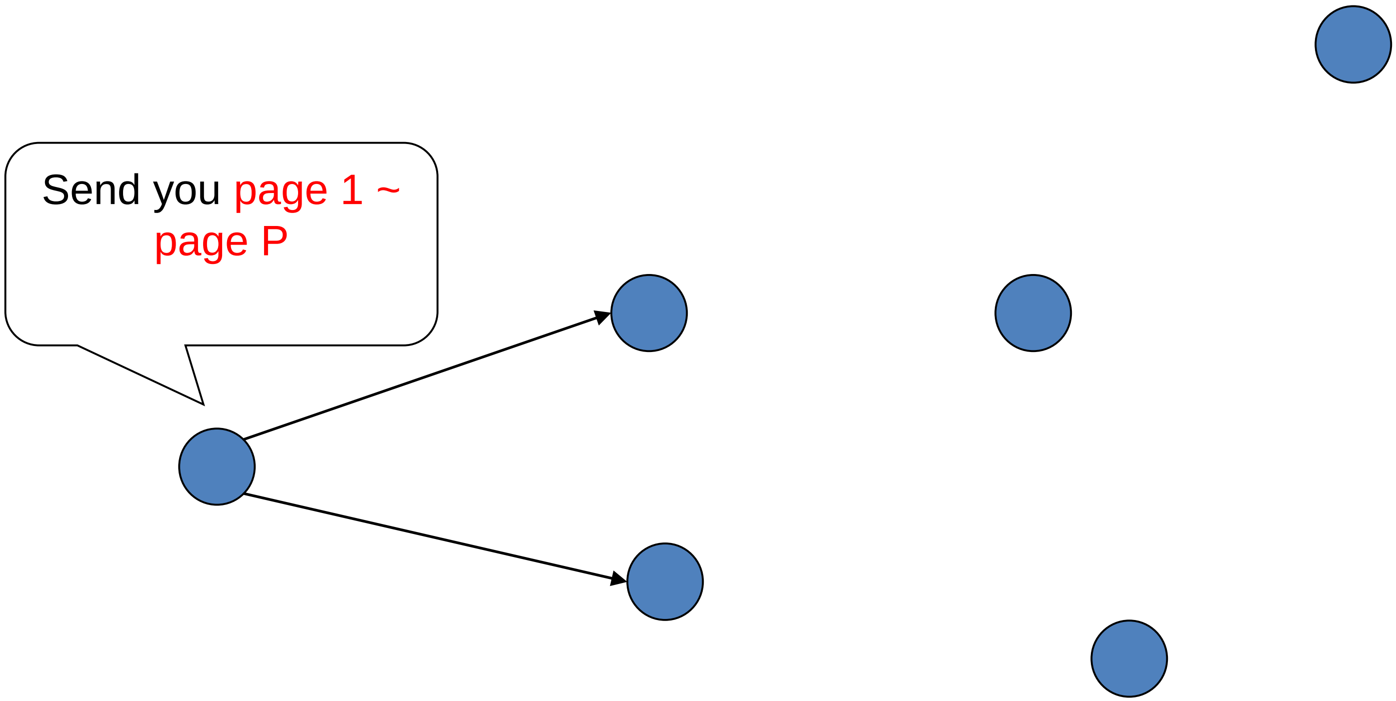
Epidemic propagation (4)

4. Neighboring nodes request data



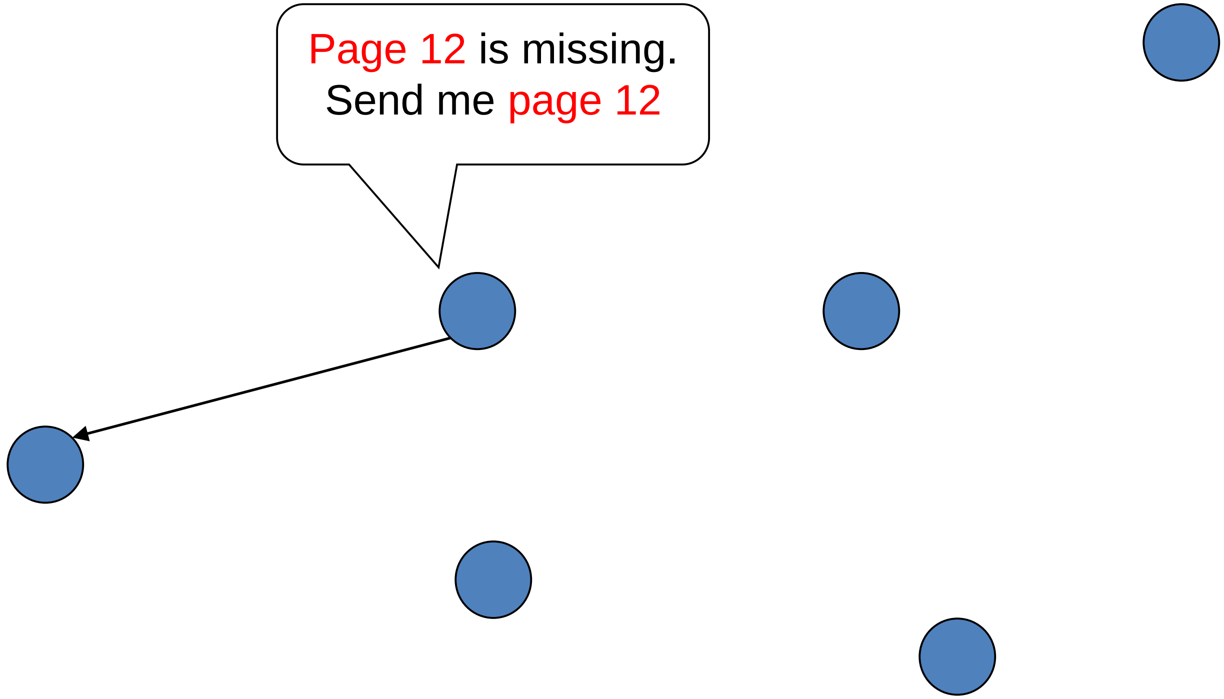
Epidemic propagation (5)

5. Transmit each page



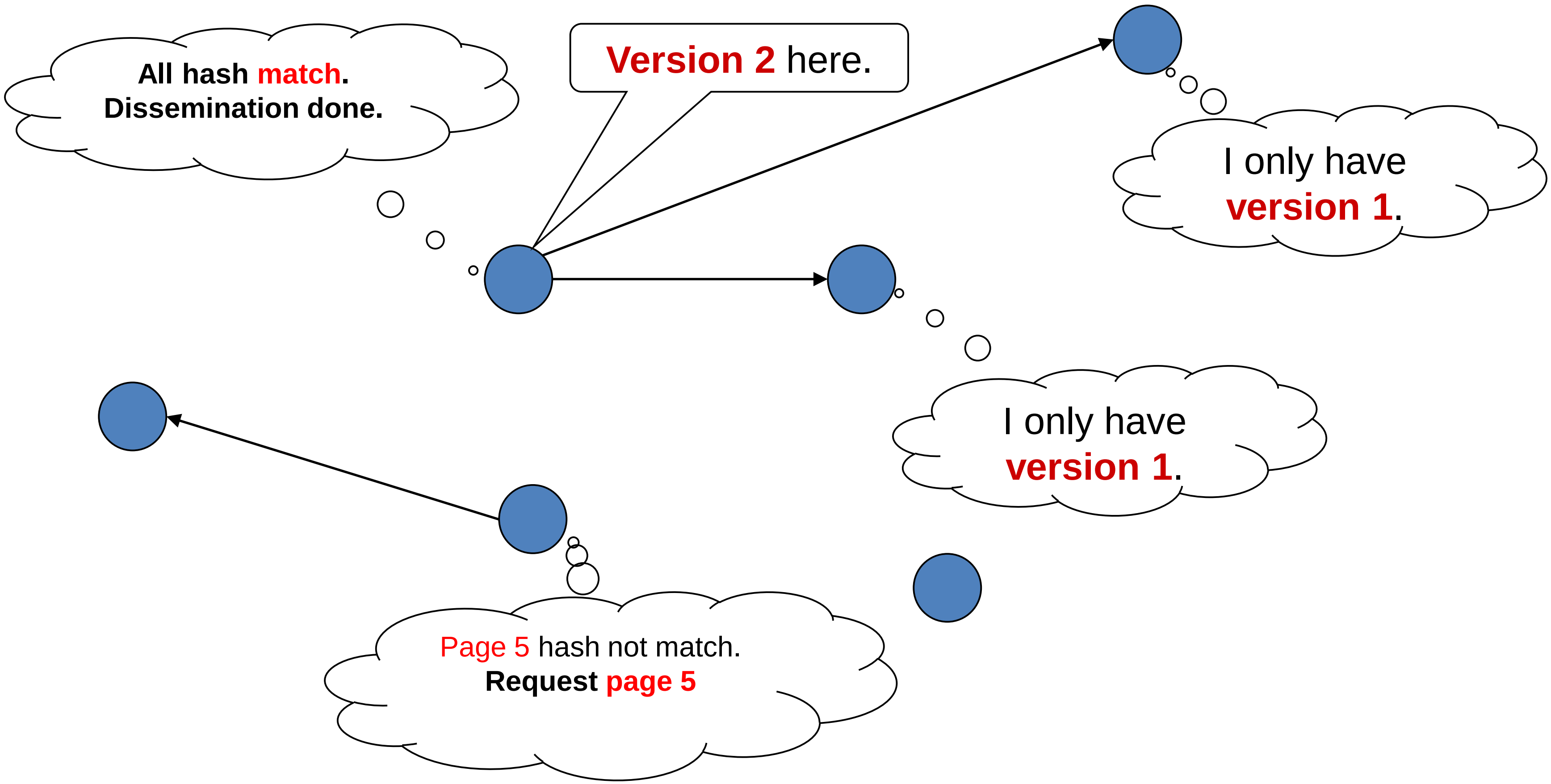
Epidemic propagation (6)

6. Nodes request missing page



Epidemic propagation (7)

7. Check hash of each page



Threat Model

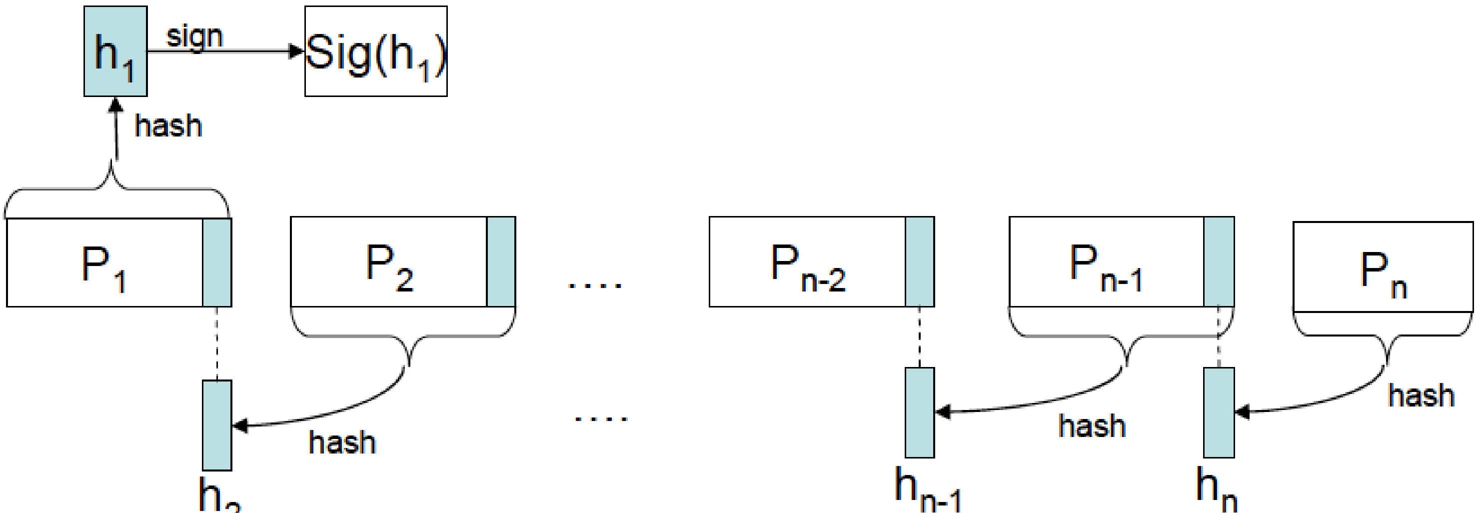
- Adversary has power laptop/computer
- External Attacks: adversary doesn’t control any node
  - Eavesdrop, inject forged messages, replay intercepted messages, impersonate valid node, *Wormhole Attack* (fake non-existing links), *Sybil Attack* (one node presents several identities to defeat fault tolerance)
- Internal Attacks: take control of nodes
  - manipulate nodes until detected, intercept sensitive information even if encrypted, (selectively) drop packets, and launch Sybil attacks
- Adversary can distribute illegal code, drain battery, disconnect network etc.

Setting: Metrics

- Security metrics
  - Can external adversary forge a message?
  - Can single or several receivers forge a message that at least one other receiver accepts?
- Efficiency metrics
  - Communication overhead
  - Computation overhead
  - Storage overhead
  - Delay for authentication / signature
  - Resilience to packet loss

Code Dissemination – Hash Chain

- Image fragmented into fixed size segments – called pages
- Calculate hash value (h_n) of last page P_n and append this to previous page P_{n-1} , until first page is reached
- Hash value of first page P1 signed with private key of base station (BS)
- Receivers verify this using public key of BS and recursively authenticate each page

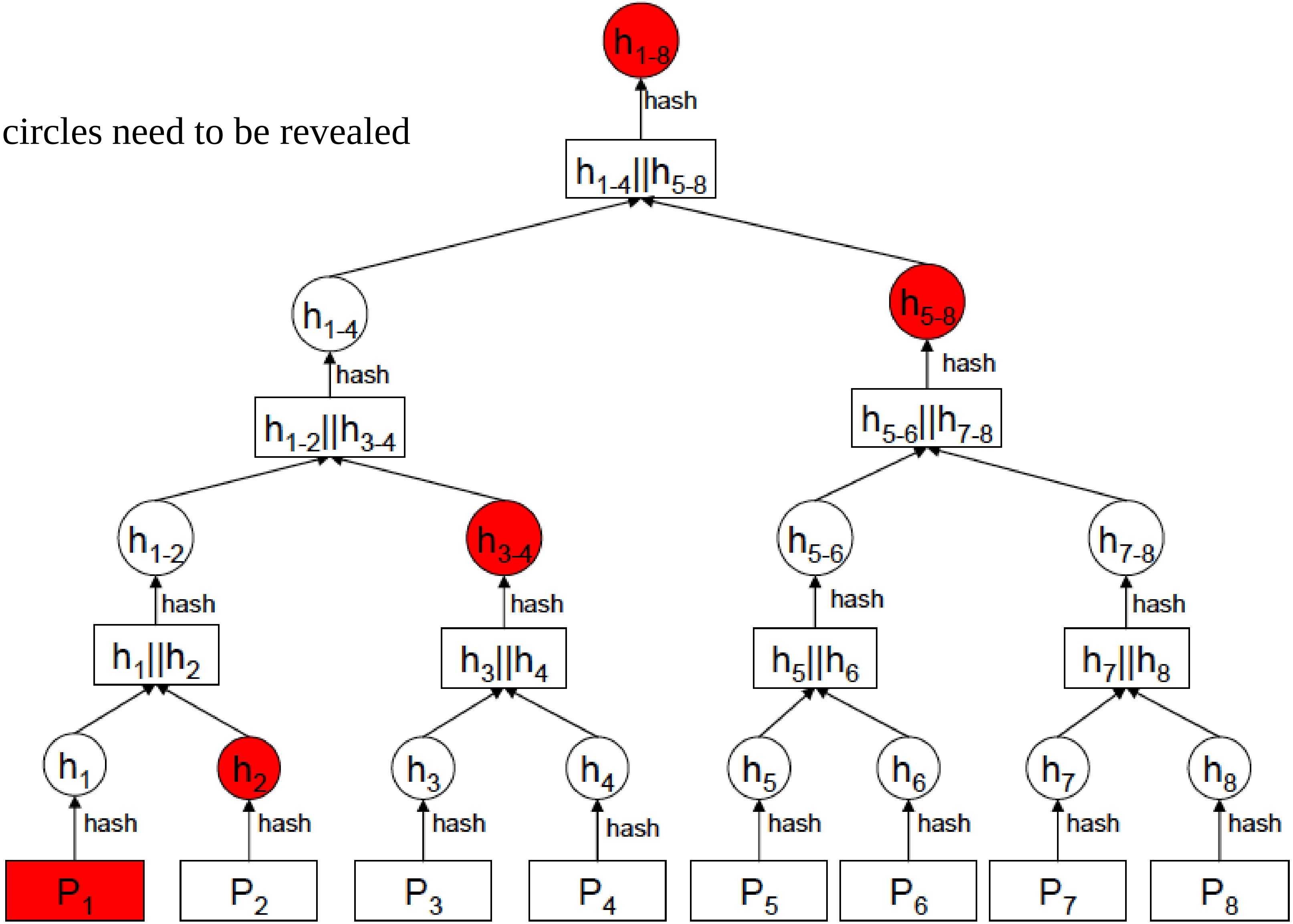


Merkle Hash Tree

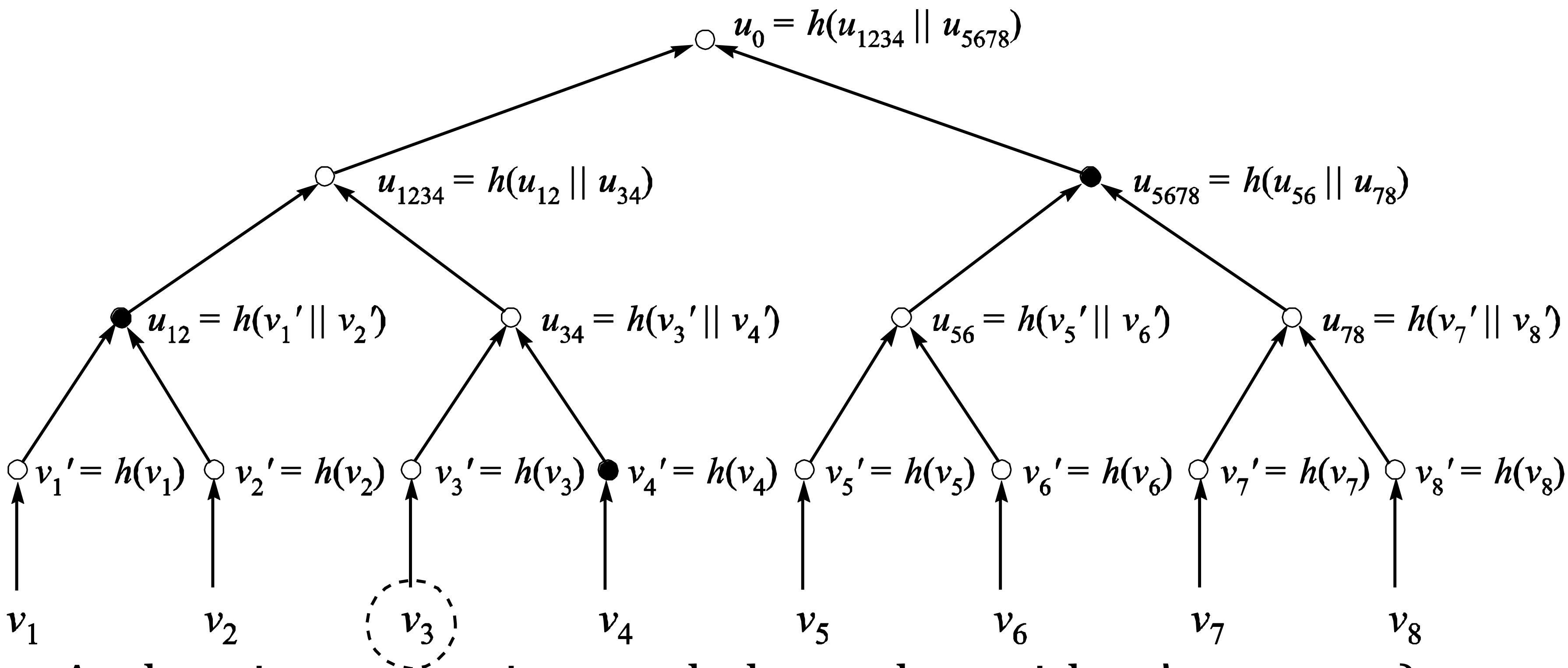
- Hash Chain elements can only be revealed sequentially
  - May not be acceptable for many applications e.g. P2P
- Merkle-trees : allowing for the pre-authentication of a set of values with a single digital signature (on the root u_0 of the tree) and for the revelation of those values in *any* order
- when revealing a value v_i, reveal all the values assigned to the sibling vertices on the path from v_i' to the root
  - One way hash property ensures: this disclosure not sufficient to calculate any other unrevealed v_j

Code Dissemination-MT Example

*Red circles need to be revealed



Merkle Tree Example



- Authenticate v_3, v_3 is revealed together with v_4', u_{12}, u_{5678})
- verifiers hash the revealed values appropriately and check if the result is u_0
  - $u_0 = H(H(u_{12} \| H(H(v_3) \| v_4')) \| u_{5678})$

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Code Dissemination - MT

- We could further divide each page into packets
- Take hash of each packet
- Construct a Merkle tree of these hash values and get root for each page
- Recursive hash value of the roots of each page is done using Hash-Chain
- Digital signature for the first root value is sent
- Along with root value, also need sibling vertices as discussed earlier

Signature Based Attack

- Signature expensive operation on small embedded devices
- Attacker keeps sending forged data
- Node depletes energy in doing signature verification
- These approaches need to know number of data-packets in advance
  - may not be available in many applications

Small RSA Signature

- Idea
  - Use short-lived small RSA keys (e.g., 384 bit)
  - Periodically send out new public key signed with strong signature
    - 48 byte signature per packet
    - Signature generation ~0.1ms, verification ~10us
- Advantages
  - Relatively low computation overhead
  - No buffering, no verification delay
  - Scalable
- Disadvantages
  - Relatively high communication overhead (> 50 bytes/packet)
  - Need time synchronization
  - Not perfectly robust to packet loss

Learning Outcomes

- Appreciate how Broadcast/multicast fundamentally changes protocol design space for authentication.
- Understand tradeoff between reliability and security
  – Key exchange etc must be reliable?
- Understand hash chain and Merkle tree algorithms and their application for security.
- Understand various threats in adhoc, wireless sensor networks and IoT
- Appreciate that different points of the design space have different "best solution"

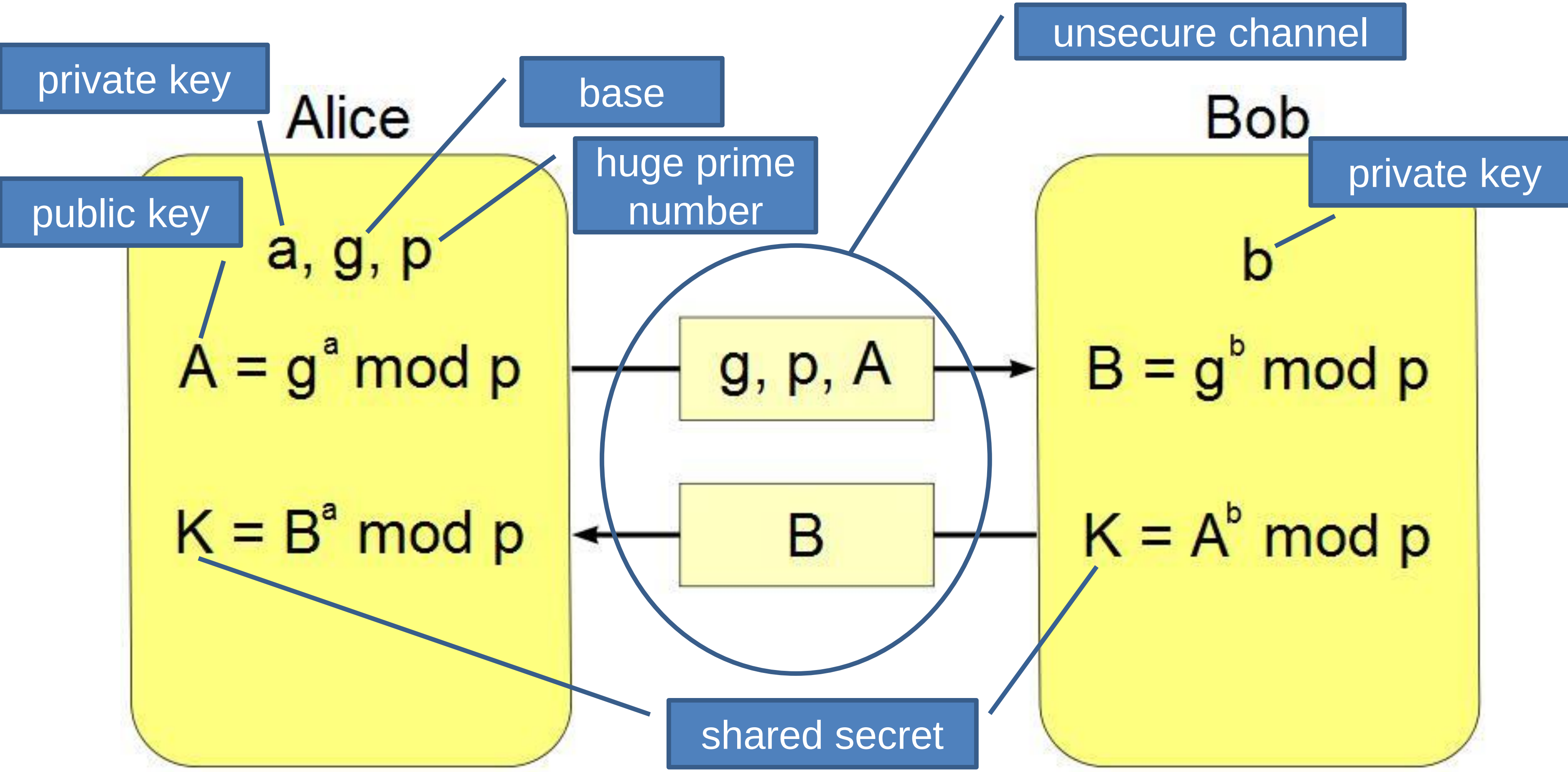
Reference List

- MERKLE TREE
  - *Appendix-A, L. Buttyan and J. P. Hubaux,* Security and Cooperation in Wireless Networks
  - *A. Perrig, R. Canetti, D. Song, and J. D. Tygar*. Efficient and secure source authentication for multicast. In *Proceedings of the Sympo- sium on Network and Distributed Systems Secu- rity (NDSS 2001)*, pages 35–46. Internet Society, February 2001
- Seluge/Deluge
  - *Sangwon Hyun, Peng Ning, An Liu, and Wenliang Du*. Seluge: Secure and dos-resistant code dissemination in wireless sensor networks. In IPSN ’08: Proceedings of the 7th international conference on Information processing in sensor networks, pages 445–456, 2008.
- A good paper on Broadcast Encryption scheme
  - D. Boneh, C. Gentry, and B. Waters. Collusion resistant broadcast encryption with short ciphertexts and private keys. In Advances in Cryptology–CRYPTO 2005, pages 258–275, 2005.

Reference (Contd)

- NaCL (Salt) Network and Cryptography Library (http://nacl.cr.yp.to)
- **RFC 4347 - Datagram Transport Layer Security**
- For interactive ECC curve etc
  - **https://www.certicom.com/ecc_tutorial/ecc_javaCurve.html**
  - ECC Video (https://www.youtube.com/watch?v=l6jTFxQaUJA)
- ACKNOWLEDGMENT: Foils contributed by Phd students Hailun Tan, Jun Kim Young
  - Some adapted from Prof Adrian Perrig.
  - ECC foils are modified from Michael Karls's version.

Diffie-Hellman key exchange



$K = A^b \bmod p = (g^a \bmod p)^b \bmod p = g^{ab} \bmod p = (g^b \bmod p)^a \bmod p = B^a \bmod p$

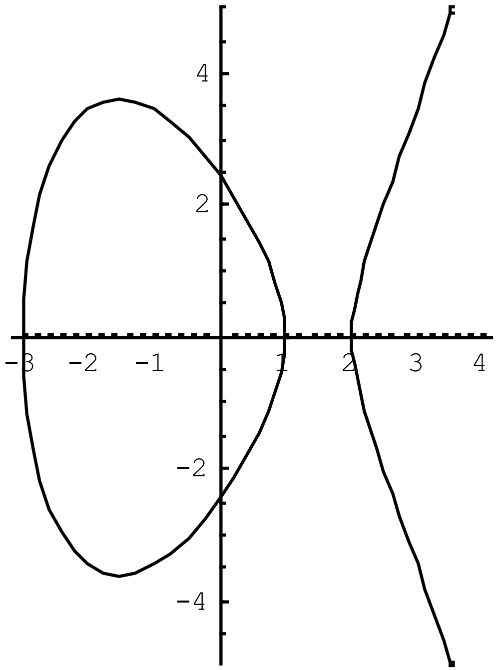
Alice’s private key = 5, Bob’s private key = 4, g=3, p=7

Alice’s public key = 3^5 mod 7 = 5, Bob’s public key = 3^4 mod 7 = 4

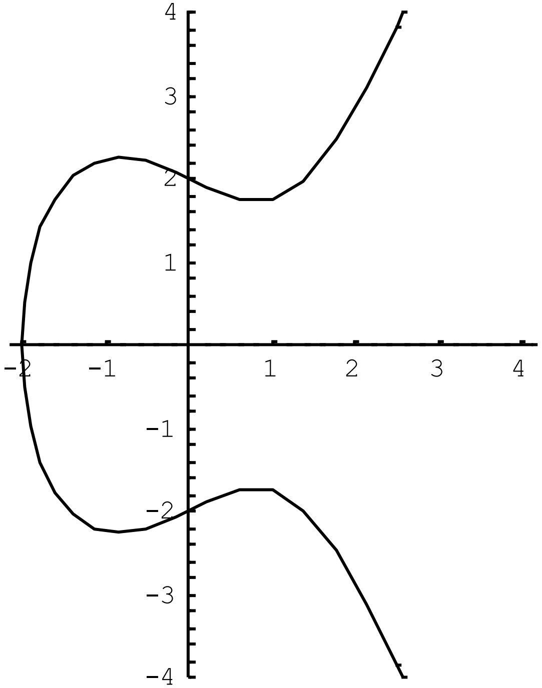
Alice’s shared key = 4^5 mod 7 = 2, Bob’s shared key = 5^4 mod 7 = 2

Examples of Elliptic Curves

- $y^2 = x^3-7x+6$



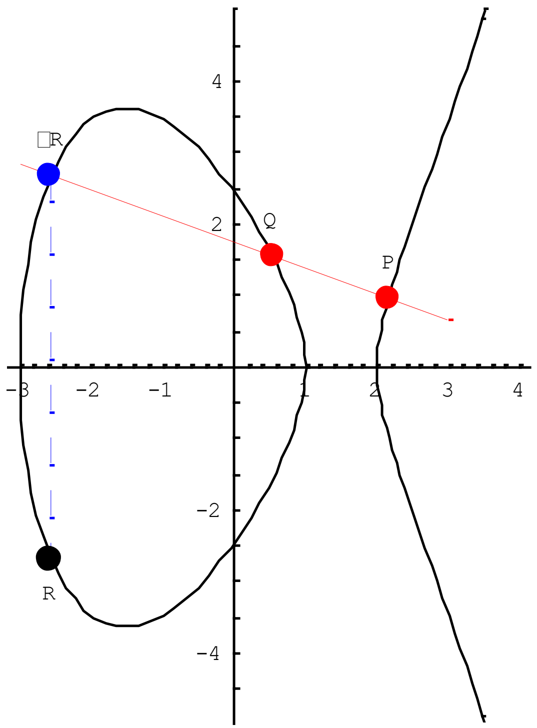
- $y^2 = x^3-2x+4$



Adding Two Points (Geometrically): $x_P \neq x_Q$

- We skip maths/algebraic details (beyond scope)
- The line L through P and Q will intersect the curve at one other point.
- Call this third point -R.
- Reflect the point -R about the x-axis to point R.
- P+Q = R

- $y^2 = x^3 - 7x + 6$



Point Doubling: $x_P=x_Q$ and $y_P = y_Q$

- Since P = Q, the line L through P and Q is tangent to the curve at P.
- Again L will intersect the curve at another point, -R.
- As in Case 1, reflect -R about the x-axis to point R.
- P+P = R
- Notation: 2P = P+P
- *Basically this computation (and variants) is more efficient than the standard Diffie-Hellman*
- *Crypto: Let P and Q be two points on an elliptic curve such that kP = Q, where k is a scalar. Given P and Q, it is hard to compute k.*

- $y^2 = x^3-7x+6$