Security and Cooperation in Wireless Networks

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Security and Cooperation in Wireless Networks

a tutorial presented at the IST Mobile Summit, Budapest, July 1, 2007.

Outline

- New wireless networks and new challenges (20')
- Thwarting malicious behavior
  - introduction to cryptography and security techniques (25')
  - naming and addressing (20')
  - key establishment (20')
  - secure routing (30')
- Thwarting selfish behavior
  - introduction to game theory (25')
  - selfishness in packet forwarding (20')
  - border games in cellular networks (20')

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New wireless networks and challenges

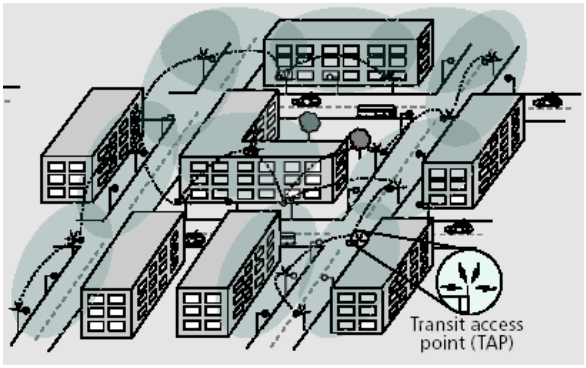
new wireless networks;
new challenges;
the issue of trust;

New wireless networks

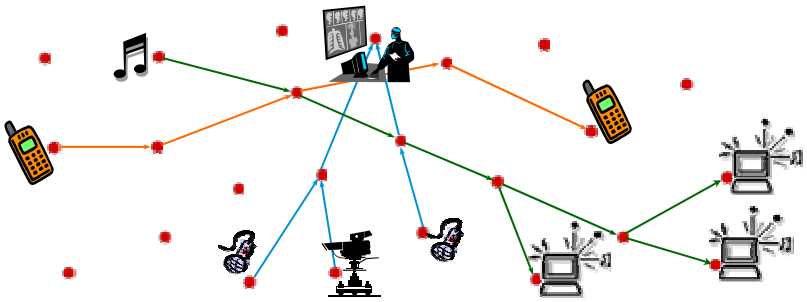
- everything beyond current wireless networks (3G and WiFi)
- examples:
  - wireless mesh networks
  - wireless community networks
  - mobile ad hoc networks
  - personal area networks
  - body area networks
  - vehicular networks
  - wireless sensor networks
  - delay tolerant networks
  - RFID systems

Wireless mesh networks

- mesh technology can be used to extend the coverage of wireless hot spots in a sizeable geographical area
- based on transit access points (mesh routers) and multi-hop wireless communications
- Internet connectivity is provided to a larger population at a lower cost



Wireless ad hoc networks



- merging terminal and router functions
- everything is potentially mobile
- initial applications: communication in the battlefield (Packet Radio Networks, in the 70's)
- potentially useful civilian applications (see next slides)
- similar trend at the application layer: peer-to-peer
  (e.g., Napster ➔ Gnutella)

Vehicular communications

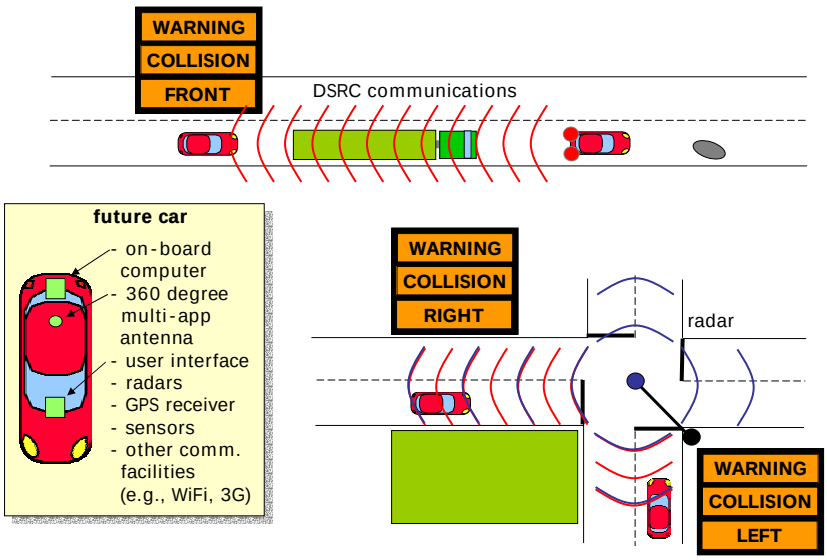
- side effects of road traffic

40000 people die and 1.5 million are injured every year in the EU

traffic jams generate a tremendous waste of time and fuel

- most of these problems could be solved by providing appropriate information to the driver or to the vehicle

Examples (C2C and I2C)

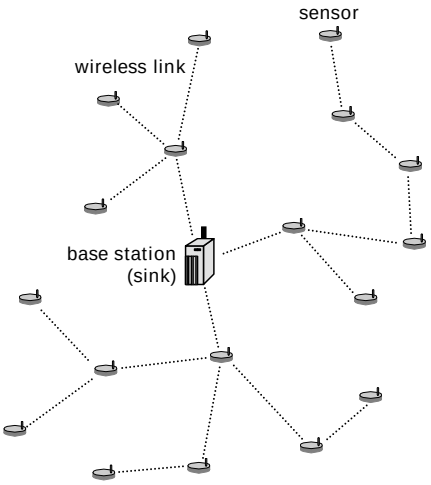


Envisioned DSRC applications for public safety

- APPROACHING EMERGENCY VEHICLE (WARNING) ASSISTANT (3)
- EMERGENCY VEHICLE SIGNAL PREEMPTION
- ROAD CONDITION WARNING
- LOW BRIDGE WARNING
- WORK ZONE WARNING
- IMMINENT COLLISION WARNING (D)
- CURVE SPEED ASSISTANCE [ROLLOVER WARNING] (1)
- INFRASTRUCTURE BASED – STOP LIGHT ASSISTANT (2)
- INTERSECTION COLLISION WARNING/AVOIDANCE (4)
- HIGHWAY/RAIL [RAILROAD] COLLISION AVOIDANCE (10)
- COOPERATIVE COLLISION WARNING [V-V] (5)
- GREEN LIGHT - OPTIMAL SPEED ADVISORY (8)
- COOPERATIVE VEHICLE SYSTEM – PLATOONING (9)
- COOPERATIVE ADAPTIVE CRUISE CONTROL [ACC] (11)
- VEHICLE BASED PROBE DATA COLLECTION (B)
- INFRASTRUCTURE BASED PROBE DATA COLLECTION
- INFRASTRUCTURE BASED TRAFFIC MANAGEMENT – [DATA COLLECTED from] PROBES (7)
- TOLL COLLECTION
- TRAFFIC INFORMATION (C)
- TRANSIT VEHICLE DATA TRANSFER (gate)
- TRANSIT VEHICLE SIGNAL PRIORITY
- EMERGENCY VEHICLE VIDEO RELAY
- MAINLINE SCREENING
- BORDER CLEARANCE
- ON-BOARD SAFETY DATA TRANSFER
- VEHICLE SAFETY INSPECTION
- DRIVER'S DAILY LOG

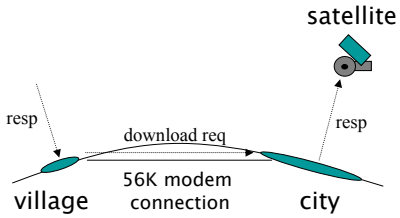
Wireless sensor networks

- environmental monitoring and disaster response
- water management
- monitoring the state of structures (e.g., bridges)
- building automation
- health monitoring of elderly and chronically ill people
- ...
- military applications

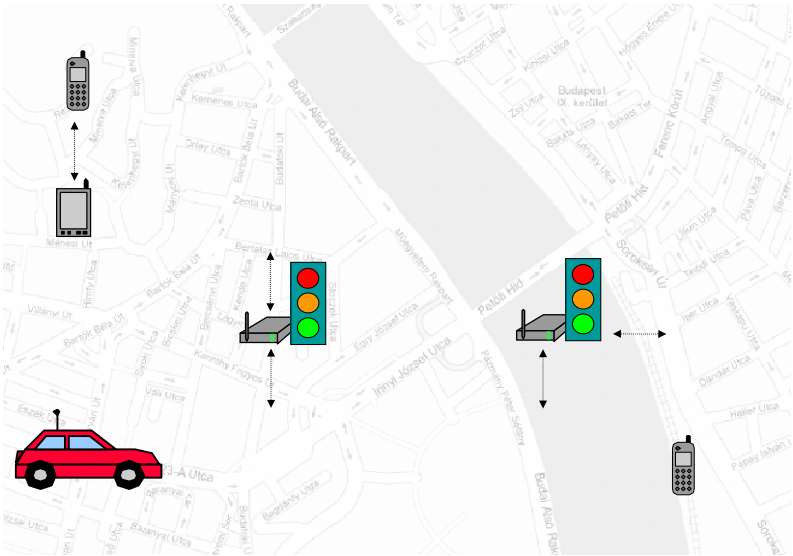


Delay tolerant networks

- node mobility, intermittent connectivity, and store-and-forward operation
- example applications:
  - Internet access to underdeveloped rural areas
  - Interplanetary Internet
  - Mobile community networks



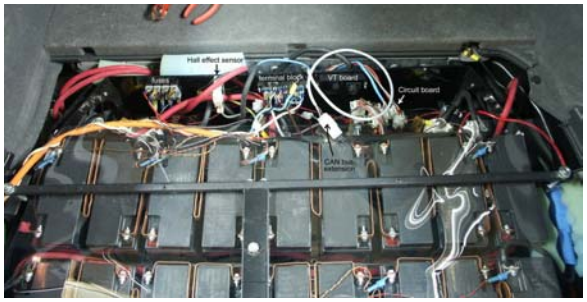
Mobile community networks



Challenges for providing security

- multi-hop wireless communications
  - why?
    - reduce interference
    - reduce energy consumption
    - save on infrastructure deployment
  - consequences
    - terminals play the role of network nodes (routers)
    - where's the edge of the network?
- lack of physical protection
  - why?
    - unattended operation
    - no tamper resistance (it would cost a lot)
  - consequences
    - easy access to devices
    - **nodes may be compromised**

Hacking your Prius [CNET News.com]



More challenges (1/2)

- scale
  - thousands or millions of nodes
  - network is not necessarily hierarchically organized
- mobility
  - dynamically changing topology
  - intermittent connectivity
  - transient relationships
- self-organization
  - infrastructureless operation
  - decentralization

More challenges (2/2)

- programmability of devices
  - easy to install new applications
  - basic operation of the device can be modified (e.g., software defined radio)
- resource constraints
  - tiny, embedded devices, running on batteries
  - no support for heavy cryptographic algorithms
  - energy consumption is an issue
- embedded systems
  - many nodes are not directly operated by humans
  - decisions must be made autonomously

Trust

- the trust model of current wireless networks is rather simple
  - subscriber – service provider model
  - subscribers trusts the service provider for providing the service, charging correctly, and not misusing transactional data
  - service providers usually do not trust subscribers, and use security measures to prevent or detect fraud
- in the upcoming wireless networks the trust model will be much more complex
  - entities play multiple roles (users can become service providers)
  - number of service providers will dramatically increase
  - user – service provider relationships will become transient
  - how to build up trust in such a volatile and dynamic environment?
- yet, trust is absolutely fundamental for the future of wireless networks
  - pervasiveness of these technologies means that all of us must rely on them in our everyday life!

Trust vs. security and cooperation

- trust preexists security
  - all security mechanisms require some level of trust in various components of the system
  - security mechanisms can help to *transfer* trust in one component to trust in another component, but they cannot create trust by themselves
- cooperation reinforces trust
  - trust is about the ability to *predict* the behavior of another party
  - cooperation (i.e., adherence to certain rules for the benefit of the entire system) makes predictions more reliable

Reasons to trust

- moral values
  - will be difficult to observe compliance with them
- experience about another party
  - relationships may not last long enough for this
- rule enforcement organizations
  - need to rely more on rule enforcement mechanisms
- **rule enforcement mechanisms**
  - prevent bad things from happening → security techniques
  - encourage desirable behavior → game theory and mechanism design

Malice and selfishness

- malice
  - willingness to do harm no matter what
- selfishness
  - overuse of common resources (network, radio spectrum, etc.) for one's own benefit
- traditionally, security is concerned only with malice
- but in the future, **malice and selfishness must be considered jointly** if we want to seriously protect wireless networks

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Introduction to cryptography and security techniques

symmetric and asymmetric key encryption;
hash functions;
MAC functions;
digital signatures;
key establishment protocols;

Introduction

- security is about how to prevent attacks, or -- if prevention is not possible -- how to detect attacks and recover from them
- an attack is a a *deliberate attempt* to compromise a system; it usually exploits weaknesses in the system's design, implementation, operation, or management
- attacks can be
  - passive
    - attempts to learn or make use of information from the system but does not affect system resources
    - examples: eavesdropping message contents, traffic analysis
    - difficult to detect, should be prevented
  - active
    - attempts to alter system resources or affect their operation
    - examples: masquerade (spoofing), replay, modification (substitution, insertion, destruction), denial of service
    - difficult to prevent, should be detected

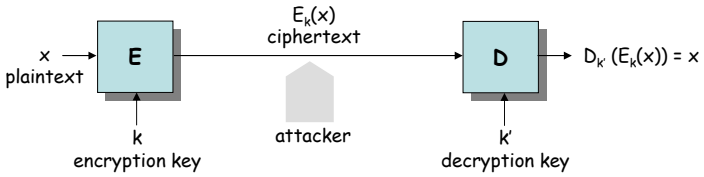
Main security services

- authentication
  - aims to detect masquerade
  - provides assurance that a communicating entity is the one that it claims to be
- access control
  - aims to prevent unauthorized access to resources
- confidentiality
  - aims to protect data from unauthorized disclosure
  - usually based on encryption
- integrity
  - aims to detect modification and replay
  - provides assurance that data received are exactly as sent by the sender
- non-repudiation
  - provides protection against denial by one entity involved in a communication of having participated in all or part of the communication
  - two basic types: non-repudiation of origin and non-repudiation of delivery

Some security mechanisms

- encryption
  - symmetric key, asymmetric (public) key
- digital signature
- access control schemes
  - access control lists, capabilities, security labels, ...
- data integrity mechanisms
  - message authentication codes, sequence numbering, time stamping, cryptographic chaining
- authentication protocols
  - passwords, cryptographic challenge-response protocols, biometrics
- traffic padding
- routing control
  - selection of physically secure routes

Operational model of encryption



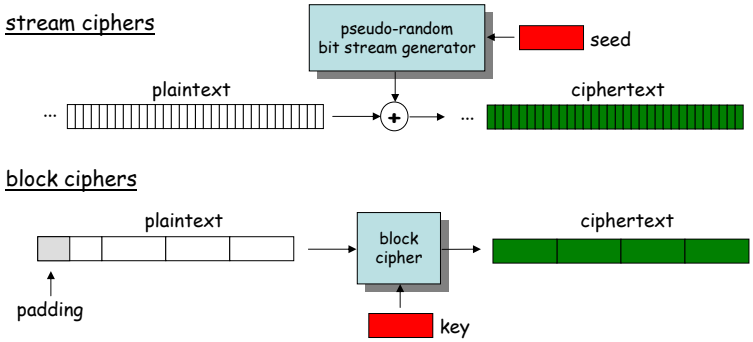
- attacker's goal:
  - to systematically recover plaintext from ciphertext
  - to deduce the (decryption) key
- Kerckhoff's assumption:
  - attacker knows all details of E and D
  - attacker doesn't know the (decryption) key

Attack models

- ciphertext-only attack
- known-plaintext attack
- (adaptive) chosen-plaintext attack
- (adaptive) chosen-ciphertext attack
- related-key attack

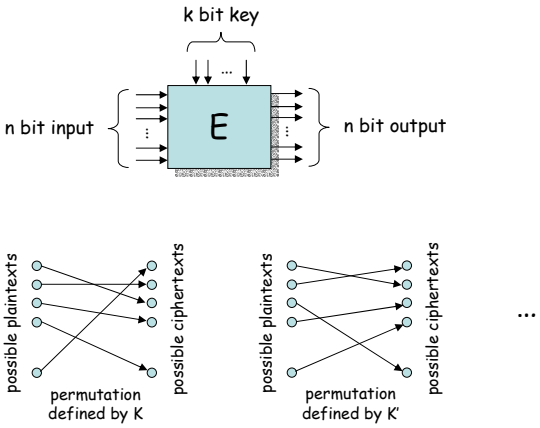
Asymmetric- vs. symmetric-key encryption

- asymmetric-key encryption
  - it is hard (computationally infeasible) to compute k' from k
  - k can be made public (public-key cryptography)
- symmetric-key encryption
  - it is easy to compute k from k' (and vice versa)
  - often k = k'
  - two main types: stream ciphers and block ciphers



Block ciphers

- an *n* bit block cipher is a function E: $\{0, 1\}^n$ x $\{0, 1\}^k$ → $\{0, 1\}^n$, such that for each K ∈ $\{0, 1\}^k$, E(X, K) = $E_K(X)$ is an invertible mapping from $\{0, 1\}^n$ to $\{0, 1\}^n$

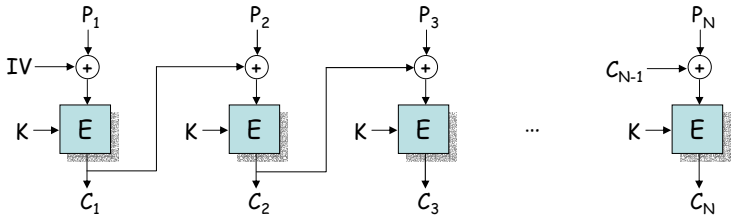


Block cipher modes of operation

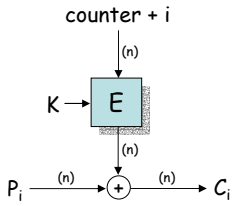
- ECB – Electronic Codebook
  - used to encipher a single plaintext block (e.g., a DES key)
- CBC – Cipher Block Chaining
  - repeated use of the encryption algorithm to encipher a message consisting of many blocks
- CFB – Cipher Feedback
  - used to encipher a stream of characters, dealing with each character as it comes
- OFB – Output Feedback
  - another method of stream encryption, used on noisy channels
- CTR – Counter
  - simplified OFB with certain advantages

Frequently used modes

- CBC



- CTR



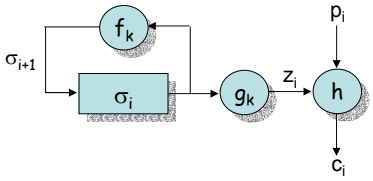
Stream ciphers

- while block ciphers simultaneously encrypt groups of characters, stream ciphers encrypt individual characters
  - may be better suited for real time applications
- stream ciphers are usually faster than block ciphers in hardware (but not necessarily in software)
- limited or no error propagation
  - may be advantageous when transmission errors are probable

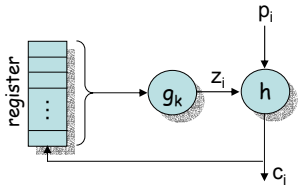
- note: the distinction between stream ciphers and block ciphers is not definitive
  - stream ciphers can be built out of block ciphers using CFB, OFB, or CTR modes
  - a block cipher in ECB or CBC mode can be viewed as a stream cipher that operates on large characters

Types of stream ciphers

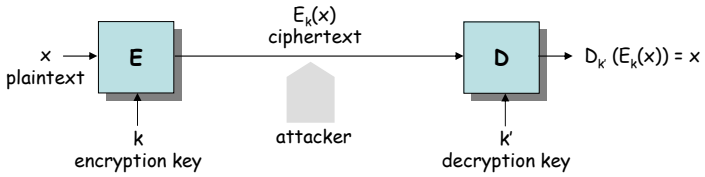
- synchronous



- self-synchronizing

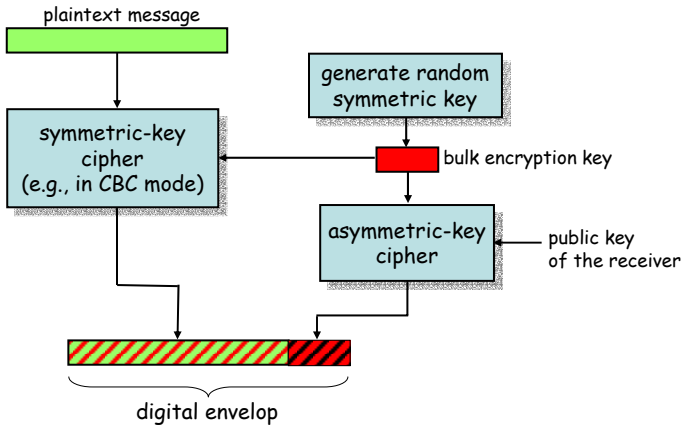


Public-key cryptography



- asymmetric-key encryption
  - it is hard (computationally infeasible) to compute k' from k
  - k can be made public (public-key cryptography)
- public-keys are not confidential but they must be authentic !
- most popular public-key encryption methods (e.g., RSA) are several orders of magnitude slower than the best known symmetric key schemes

Digital enveloping

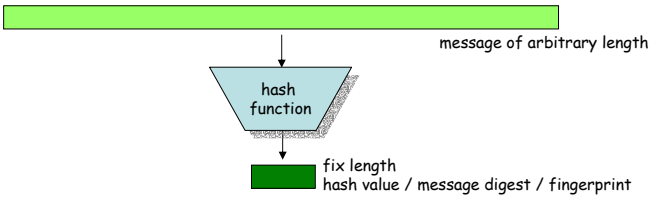


Examples for hard problems

- factoring problem
  - given a positive integer n, find its prime factors
    - true complexity is unknown
    - it is believed that it does not belong to P
- discrete logarithm problem
  - given a prime p, a generator g of Z_p^*, and an element y in Z_p^*, find the integer x, $0 \leq x \leq p-2$, such that $g^x \bmod p = y$
    - true complexity is unknown
    - it is believed that it does not belong to P
- Diffie-Hellman problem
  - given a prime p, a generator g of Z_p^*, and elements $g^x \bmod p$ and $g^y \bmod p$, find $g^{xy} \bmod p$
    - true complexity is unknown
    - it is believed that it does not belong to P

Hash functions

- a hash function maps bit strings of arbitrary finite length to bit strings of fixed length (n bits)
- many-to-one mapping → collisions are unavoidable
- however, finding collisions are difficult → the hash value of a message can serve as a compact representative image of the message (similar to fingerprints)

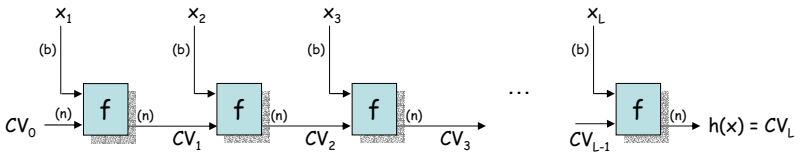


Desirable properties of hash functions

- ease of computation
  - given an input x, the hash value h(x) of x is easy to compute
- weak collision resistance (2nd preimage resistance)
  - given an input x, it is computationally infeasible to find a second input x' such that h(x') = h(x)
- strong collision resistance (collision resistance)
  - it is computationally infeasible to find any two distinct inputs x and x' such that h(x) = h(x')
- one-way hash function (preimage resistance)
  - given a hash value y (for which no preimage is known), it is computationally infeasible to find any input x s.t. h(x) = y

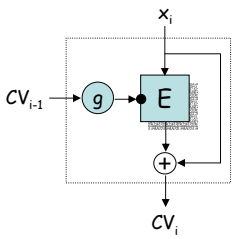
Iterated hash functions

- input is divided into fixed length blocks
- last block is padded if necessary
- each input block is processed according to the following scheme

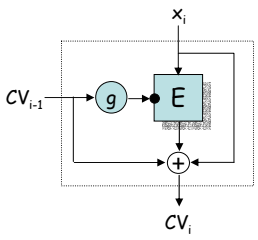


Hash functions based on block ciphers

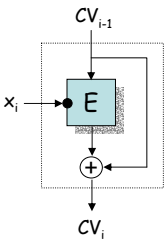
Matyas - Meyer - Oseas



Miyaguchi-Preneel

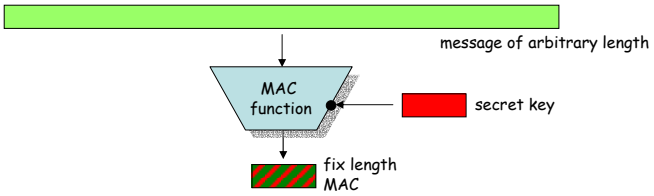


Davies - Meyer

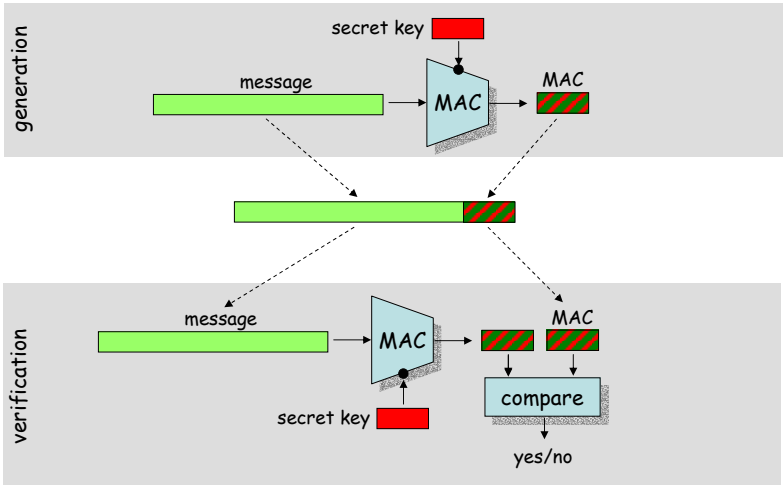


Message authentication codes (MACs)

- MAC functions can be viewed as hash functions with two functionally distinct inputs: a message and a secret key
- they produce a fixed size output (say n bits) called the MAC
- practically it should be infeasible to produce a correct MAC for a message without the knowledge of the secret key
- MAC functions can be used to implement data integrity and message origin authentication services



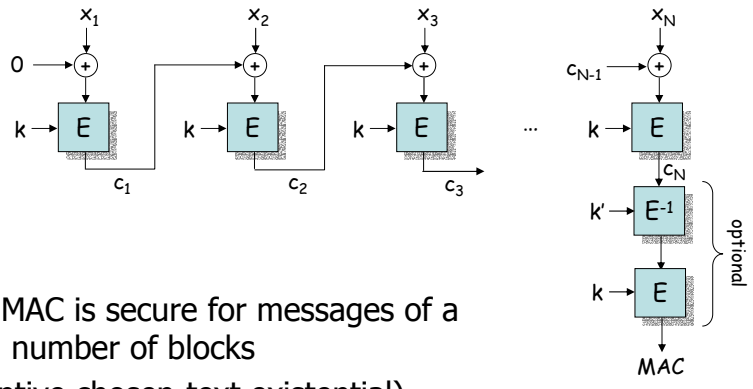
MAC generation and verification



Desirable properties of MAC functions

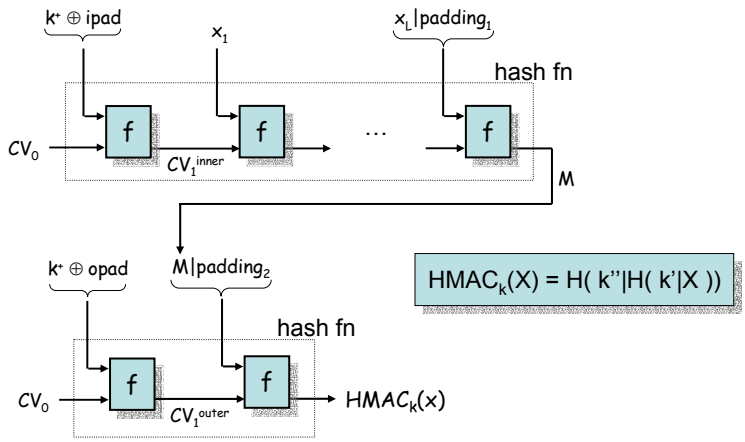
- ease of computation
  - given an input x and a secret key k, it is easy to compute $MAC_k(x)$
- key non-recovery
  - it is computationally infeasible to recover the secret key k, given one or more text-MAC pairs $(x_i, MAC_k(x_i))$ for that k
- computation resistance
  - given zero or more text-MAC pairs $(x_i, MAC_k(x_i))$, it is computationally infeasible to find a text-MAC pair $(x, MAC_k(x))$ for any new input $x \neq x_i$
  - computation resistance implies key non-recovery but the reverse is not true in general

CBC MAC



- CBC MAC is secure for messages of a fixed number of blocks
- (adaptive chosen-text existential) forgery is possible if variable length messages are allowed

HMAC

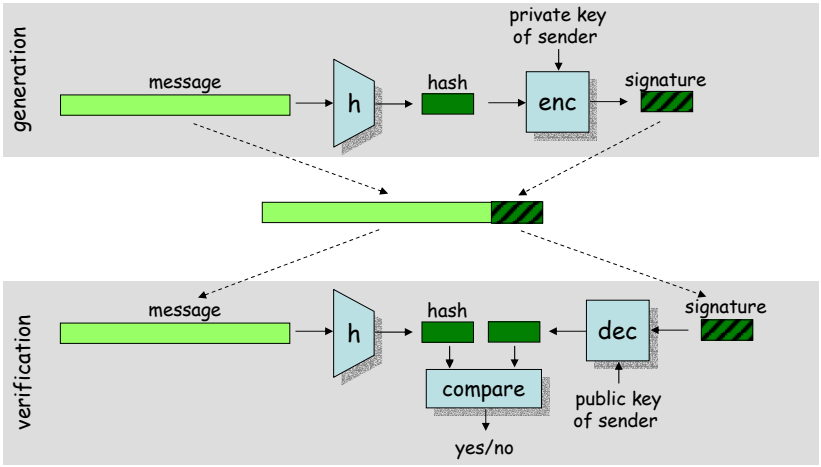


Digital signatures

- similar to MACs but
  - unforgeable by the receiver
  - verifiable by a third party
- used for message authentication and non-repudiation (of message origin)
- based on public-key cryptography
  - private key defines a signing transformation S_A
    - $S_A(m) = \sigma$
  - public key defines a verification transformation V_A
    - $V_A(m, \sigma)$ = true if $S_A(m) = \sigma$
    - $V_A(m, \sigma)$ = false otherwise

"Hash-and-sign" paradigm

- public/private key operations are slow
- hash the message first and apply public/private key operations to the hash value only



Key establishment protocols

- goal of key establishment protocols
  - to setup a shared secret between two (or more) parties
  - it is desired that the secret established by a fixed pair of parties varies on subsequent executions of the protocol (dynamicity)
  - established shared secret is used as a *session key* to protect communication between the parties
- motivation for use of session keys
  - to limit available ciphertext for cryptanalysis
  - to limit exposure caused by the compromise of a session key
  - to avoid long-term storage of a large number of secret keys (keys are created on-demand when actually required)
  - to create independence across communication sessions or applications

Basic classification

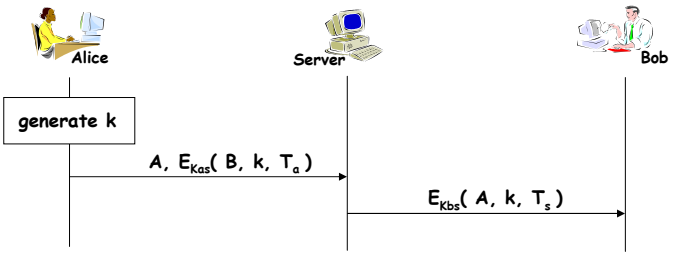
- key transport protocols
  - one party creates or otherwise obtains a secret value, and securely transfers it to the other party
- key agreement protocols
  - a shared secret is derived by the parties as a function of information contributed by each, such that no party can predetermine the resulting value

Further services

- entity authentication
- implicit key authentication
  - one party is assured that no other party aside from a specifically identified second party (and possibly some trusted third parties) may gain access to the established session key
- key confirmation
  - one party is assured that a second (possibly unidentified) party actually possesses the session key
  - possession of a key can be demonstrated by
    - producing a one-way hash value of the key or
    - encryption of known data with the key
- key freshness
  - one party is assured that the key is new (never used before)

The Wide-Mouth-Frog protocol

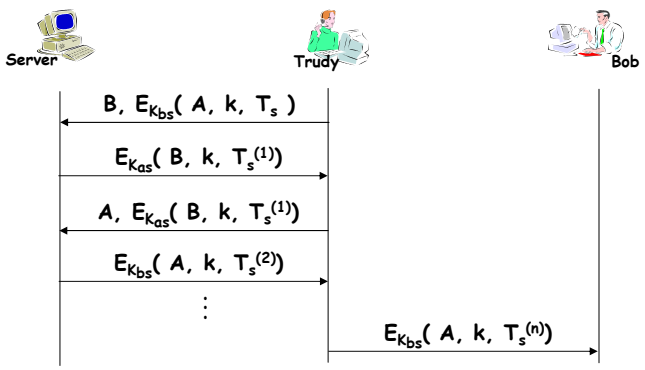
summary: a simple **key transport protocol** that uses a trusted third party
Alice generates the session key and sends it to Bob via the trusted third party



characteristics: implicit key authentication for Alice
explicit key authentication for Bob
key freshness for Bob with timestamps (flawed)
unilateral entity authentication of Alice
on-line third party (Server) trusted for secure relaying of keys and verification of freshness,
in addition A is trusted for generating good keys
initial long-term keys between the parties and the server are required

A flaw in the Wide-Mouth-Frog protocol

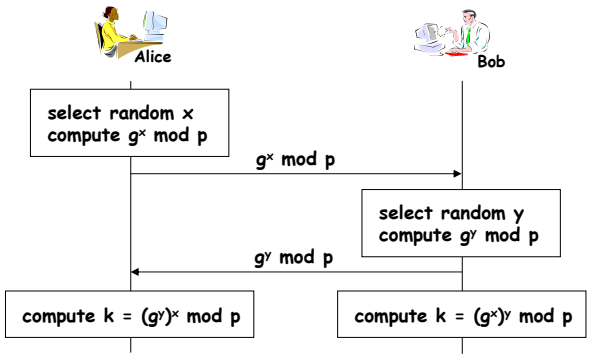
summary: after observing one run of the protocol, Trudy can continuously use the Server as an oracle until she wants to bring about re-authentication between Alice and Bob



The Diffie-Hellman protocol

summary: a **key agreement protocol** based on one-way functions; in particular, security of the protocol is based on the hardness of the discrete logarithm problem and that of the Diffie-Hellman problem

assumptions: p is a large prime, g is a generator of Z_p^*, both are publicly known system parameters



characteristics: NO AUTHENTICATION, key freshness with randomly selected exponents, no party can control the key, no need for a trusted third party

Summary

- security services are implemented by using security mechanisms
- many security mechanisms are based on cryptography (e.g., encryption, digital signature, some data integrity mechanisms, some authentication schemes, etc.)
- but be cautious:

  "If you think cryptography is going to solve your problem, you don't understand cryptography and you don't understand your problem."

  -- Bruce Schneier
- other important aspects are
  - physical protection
  - procedural rules
  - education

Security and Cooperation in Wireless Networks

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Naming and addressing

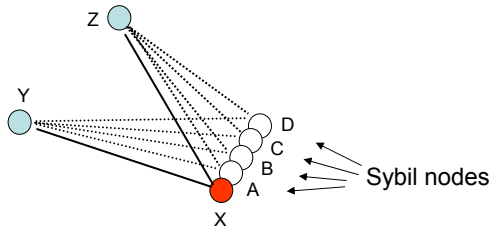
attacks against naming and addressing:
- address stealing
- Sybil attack
- node replication attack;

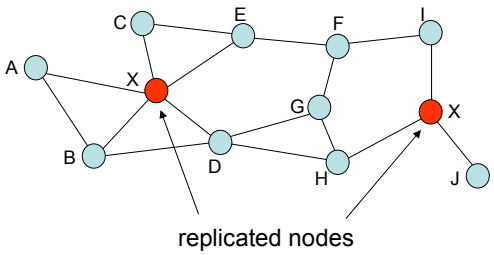
protection mechanisms:
- Cryptographically Generated Addresses
- witness based detection of node replication

Introduction

- naming and addressing are fundamental for networking
  - notably, routing protocols need addresses to route packets
  - services need names in order to be identifiable, discoverable, and useable
- attacks against naming and addressing
  - address stealing
    - adversary starts using an address already assigned to and used by a legitimate node
  - Sybil attack
    - a single adversarial node uses several invented addresses
    - makes legitimate nodes believe that there are many other nodes around
  - node replication attack
    - dual of the Sybil attack
    - the adversary introduces replicas of a single compromised node using the same address at different locations of the network

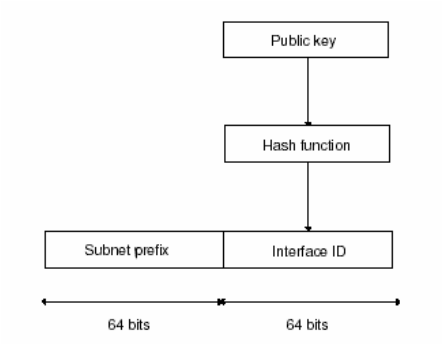
Illustration of the Sybil and node replication attacks





Cryptographically Generated Addresses (CGA)

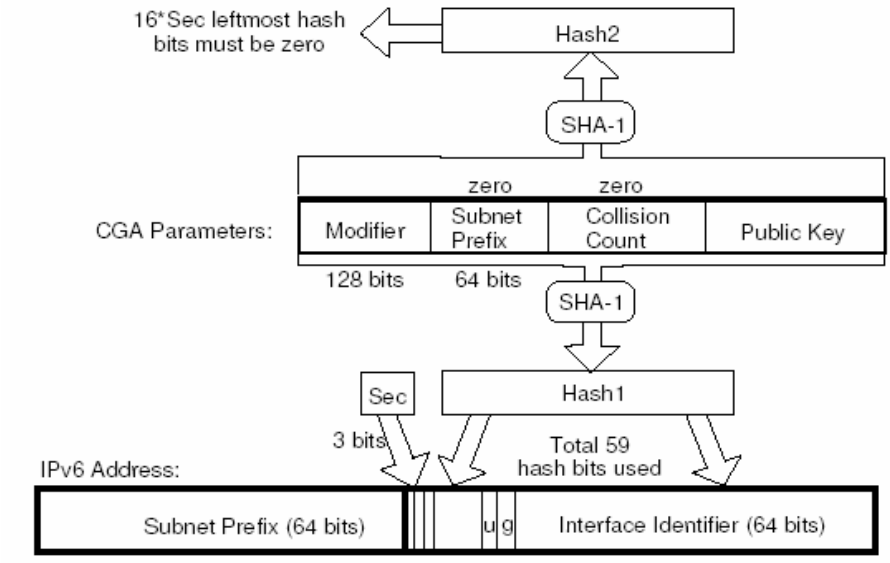
- aims at preventing address stealing
- general idea:
  - generate node address from a public key
  - corresponding private key is known only by the legitimate node
  - prove ownership of the address by proving knowledge of the private key
- example in case of IPv6:



A potential problem with CGA

- often only a limited number of bits of the address can be chosen arbitrarily (64 in our example)
- this number may be too small to guarantee second pre-image resistance
  - an adversary could pre-compute a large database of interface identifiers from public keys generated by himself, and use this database to find matches to victims' addresses
- a solution can be the technique called *hash extension*
  - increase the cost of address generation, and hence the cost of brute-force attacks, while keep constant the cost of address usage and verification

Hash extension



Protocol for CGA generation

1. Set the modifier field to a random 128-bit value.
2. Hash the concatenation of the modifier, 64+8 zero bits, and the encoded public key. The leftmost 112 bits of the result are Hash2.
3. Compare the 16*Sec leftmost bits of Hash2 with zero. If they are all zero (or if Sec=0), continue with Step (4). Otherwise, increment the modifier and go back to Step (2).
4. Set the collision count value to zero.
5. Hash the concatenation of the modifier, subnet prefix, collision count and encoded public key. The leftmost 64 bits of the result are Hash1.
6. Form an interface identifier by setting the two reserved bits in Hash1 both to 1 and the three leftmost bits to the value Sec.
7. Concatenate the subnet prefix and interface identifier to form a 128-bit IPv6 address.
8. If an address collision with another node within the same subnet is detected, increment the collision count and go back to step (5). However, after three collisions, stop and report the error.

Protocol for CGA verification

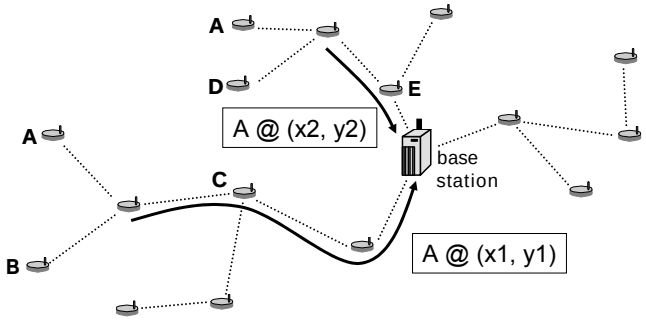
1. Check that the collision count value is 0, 1 or 2, and that the subnet prefix value is equal to the subnet prefix (i.e. leftmost 64 bits) of the address. The CGA verification fails if either check fails.
2. Hash the concatenation of the modifier, subnet prefix, collision count and the public key. The 64 leftmost bits of the result are Hash1.
3. Compare Hash1 with the interface identifier (i.e. the rightmost 64 bits) of the address. Differences in the two reserved bits and in the three leftmost bits are ignored. If the 64-bit values differ (other than in the five ignored bits), the CGA verification fails.
4. Read the security parameter Sec from the three leftmost bits of the interface identifier of the address.
5. Hash the concatenation of the modifier, 64+8 zero bits and the public key. The leftmost 112 bits of the result are Hash2.
6. Compare the 16*Sec leftmost bits of Hash2 with zero. If any one of these is nonzero, CGA verification fails. Otherwise, the verification succeeds.

Thwarting the Sybil attack

- note that CGAs do not prevent the Sybil attack
  - an adversary can still generate addresses for herself
- a solution based on a central and trusted authority
  - the central authority vouches for the one-to-one mapping between an address and a device
  - e.g., a server can respond to requests concerning the legitimacy of a given address
- other solutions take advantage of some physical aspects
  - e.g., identify the same device based on radio fingerprinting

Thwarting the node replication attack (1/2)

- a centralized solution
  - each node reports its neighbors' claimed locations to a central authority (e.g., the base station in sensor networks)
  - the central authority detects if the same address appears at two different locations
  - assumes location awareness of the nodes



Thwarting the node replication attack (2/2)

- a decentralized variant
  - neighbors' claimed location is forwarded to *witnesses*
  - witnesses are randomly selected nodes of the network
  - if a witness detects the same address appearing at two different locations then it broadcast this information and the replicated nodes are revoked

Analysis of the decentralized variant

- total number if nodes is n
- average number of neighbors is d
- each neighbor of A forwards A's location claim with probability p to g randomly selected witnesses
- average number of witnesses receiving A's location claim is p*d*g
- if there are L replicas of A, then for the probability of detection:

$$P_{det} > 1 - \exp(- L(L-1)(pdg)^2 / 2n)$$

- numerical example:

  n = 10000, d = 20, g = 100, p = 0.5

  L = 2 → $P_{det} \sim 0.63$

  L = 3 → $P_{det} \sim 0.95$

Conclusions

- there are various attacks against naming and addressing
  - address stealing
  - Sybil attack
  - node replication attack
- decentralization and lack of a central authority renders the defense against these attacks difficult
- proposed solutions (CGA, node replication detection using witnesses) provide only probabilistic guarantees
  - parameters should be chosen carefully

Security and Cooperation in Wireless Networks

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Key establishment

key establishment in ad hoc networks based on
- physical contact
- vicinity
- mobility;

random key pre-distribution in sensor networks;

Key establishment in ad hoc networks

- ad hoc networks are peer-to-peer networks
- no single trusted third party is available
  - no key distribution center (KDC)
  - no certificate authority (CA)
- traditional key establishment protocols cannot be used
- however, we can take advantage of
  - physical contact
  - vicinity
  - mobility

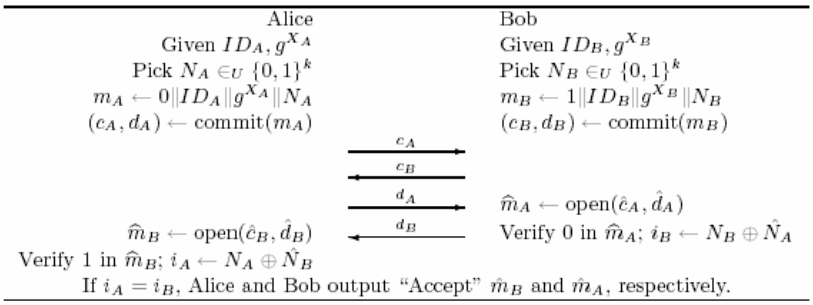
Exploiting physical contact

- target scenarios
  - modern home with multiple remotely controlled devices
    - DVD, VHS, HiFi, doors, air condition, lights, alarm, …
  - modern hospital
    - mobile personal assistants and medical devices, such as thermometers, blood pressure meters, …
- common in these scenarios
  - transient associations between devices
  - physical contact is possible for initialization purposes
- the ***resurrecting duckling*** security policy
  - at the beginning, each device has an empty *soul*
  - each empty device accepts the first device to which it is physically connected as its master (imprinting)
  - during the physical contact, a device key is established
  - the master uses the device key to execute commands on the device, including the *suicide* command
  - after suicide, the device returns to its empty state and it is ready to be imprinted again

Exploiting vicinity

- problem
  - how to establish a shared key between two PDAs?
- assumptions
  - no CA, no KDC
  - PDAs can use short range radio communications (e.g., Bluetooth)
  - PDAs have a display
  - PDAs are held by human users
- idea
  - use the Diffie-Hellman key agreement protocol
  - ensure key authentication by the human users

Diffie-Hellman with String Comparison



theorem: the probability that an attacker succeeds against the above protocol is bounded by $n\gamma 2^{-k}$, where n is the total number of users, γ is the maximum number of sessions that any party can participate in, and k is the security parameter

Integrity Codes

- is it possible to rely on the radio channel only?
- assumption
  - it is possible to implement a channel with the following property:
    - bit 0 can be turned into bit 1
    - bit 1 cannot be turned into bit 0
  - an example:
    - bit 1 = presence of random signal (~noise)
    - bit 0 = no signal at all
- i(ntegrity)-codes
  - each codeword has the same number of 0s and 1s
  - such a codeword cannot be modified in an unnoticeable way
  - encoding messages with i-codes ensures the integrity of the communications → Man-in-the-Middle is excluded

Exploiting mobility

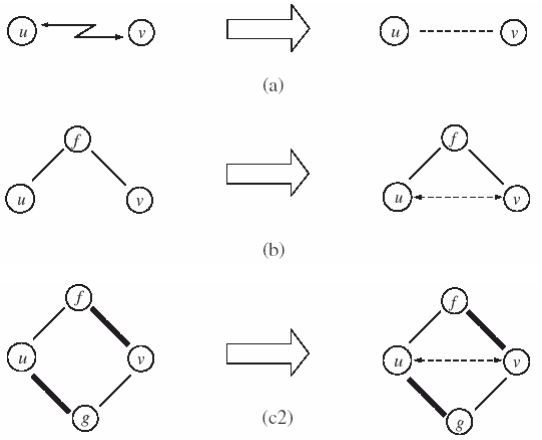
- problem
  - how to secure a whole network without a trusted third party?
- assumptions
  - when in the vicinity of each other, nodes can use a ***secure side channel*** (e.g., infra red) to setup a security association
  - each node has some ***friends*** (peers that are trusted by the node)
  - there is already a security association between friends
- mechanisms

  (a) establishment of an SA through the secure side channel

  (b) establishment of an SA through a common friend

  (c) combination of (a) and (b)

Mechanisms illustrated



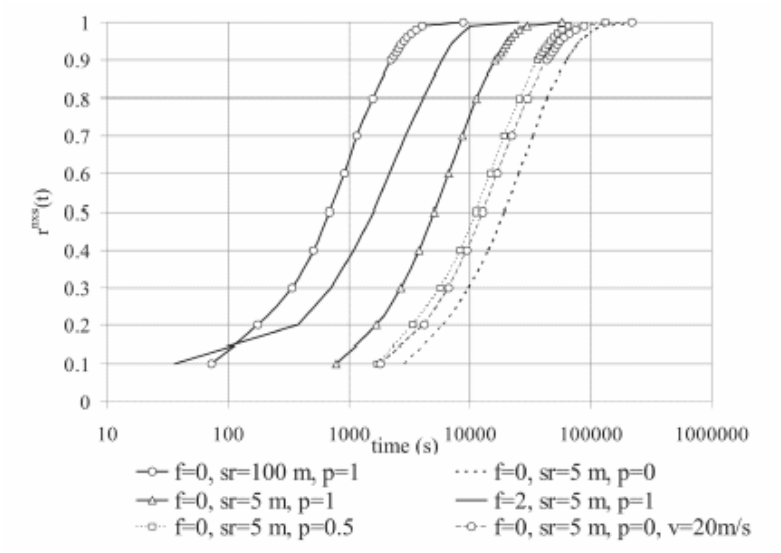
Friend-assisted SA establishment

$$
\begin{aligned}
&\text{msg1}\ \ u \rightarrow v : f, r_u \\
&\text{msg2}\ \ v \rightarrow u : g, r_v \\
&\text{msg3}\ \ u \rightarrow g : u, \{d_{u \rightarrow g}, req, v, k_u, r_v\} k_{ug} \\
&\text{msg4}\ \ g \rightarrow v : g, \{d_{g \rightarrow v}, rep, u, k_u, r_v\} k_{vg} \\
&\text{msg3}'\ v \rightarrow f : v, \{d_{v \rightarrow f}, req, u, k_v, r_u\} k_{vf} \\
&\text{msg4}'\ f \rightarrow u : f, \{d_{f \rightarrow u}, rep, v, k_v, r_u\} k_{uf} \\
&\qquad\quad u, v\ \ : k_{uv} = h(k_u, k_v)
\end{aligned}
$$

notes:

- single trusted party is replaced with two parties trusted by one entity each
- if f and g are not colluding, then they cannot compute k_{uv}
- both u and v trust at least one of f and g for not colluding

Speed of SA establishment



Key establishment in sensor networks

- due to resource constraints, asymmetric key cryptography should be avoided in sensor networks
- we aim at setting up symmetric keys

- requirements for key establishment depend on
  - communication patterns to be supported
    - unicast
    - local broadcast
    - global broadcast
  - need for supporting in-network processing
  - need to allow passive participation

- necessary key types
  - node keys – shared by a node and the base station
  - link keys – pairwise keys shared by neighbors
  - cluster keys – shared by a node and all its neighbors
  - network key – a key shared by all nodes and the base station

Setting up node, cluster, and network keys

- node key
  - can be preloaded into the node before deployment
- cluster key
  - can be generated by the node and sent to each neighbor individually protected by the link key shared with that neighbor
- network key
  - can also be preloaded in the nodes before deployment
  - needs to be refreshed from time to time (due to the possibility of node compromise)
    - neighbors of compromised nodes generate new cluster keys
    - the new cluster keys are distributed to the non-compromised neighbors
    - the base station generates a new network key
    - the new network key is distributed in a hop-by-hop manner protected with the cluster keys

Design constraints for link key establishment

- network lifetime
  - severe constraints on energy consumption
- hardware limits
  - 8-bit CPU, small memory
  - large integer arithmetics are infeasible
- no tamper resistance
  - nodes can be compromised
  - secrets can be leaked
- no a priori knowledge of post-deployment topology
  - it is not known a priori who will be neighbors
- gradual deployment
  - need to add new sensors after deployment

Traditional approaches

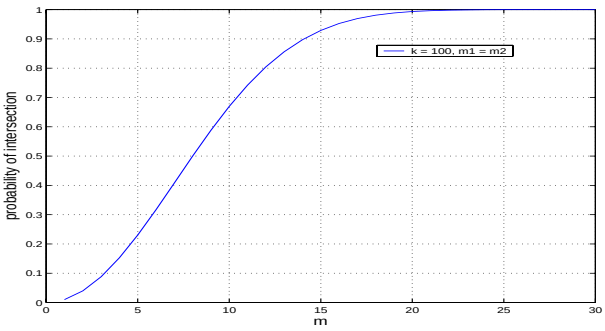
- use of public key crypto (e.g., Diffie-Hellman)
  - limited computational and energy resources of sensors
- use of a trusted key distribution server (Kerberos-like)
  - base station could play the role of the server
  - requires routing of key establishment messages to and from the base station
    - routing may already need link keys
    - unequal communication load on the sensors
  - base station becomes single point of failure
- pre-loaded link keys in sensors
  - post-deployment topology is unknown
  - single "mission key" approach
    - vulnerable to single node compromise
  - *n* -1 keys in each of the *n* sensors
    - excessive memory requirements
    - gradual deployment is difficult
    - doesn't scale

Random key pre-distribution – Preliminaries

Given a set S of k elements, we randomly choose two subsets S_1 and S_2 of m_1 and m_2 elements, respectively, from S.

The probability of $S_1 \cap S_2 \neq \varnothing$ is

$$\Pr\{S_1 \cap S_2 \neq \emptyset\} = 1 - \frac{(k-m_1)!(k-m_2)!}{k!(k-m_1-m_2)!}$$



The basic random key pre-distribution scheme

- initialization phase
  - a large pool S of unique keys are picked at random
  - for each node, m keys are selected randomly from S and pre-loaded in the node (key ring)
- direct key establishment phase
  - after deployment, each node finds out with which of its neighbors it shares a key (e.g., each node may broadcast the list of its key IDs)
  - two nodes that discover that they share a key verify that they both actually posses the key (e.g., execute a challenge-response protocol)
- path key establishment phase
  - neighboring nodes that do not have a common key in their key rings establish a shared key through a path of intermediaries
  - each link of the path is secured in the direct key establishment phase

Setting the parameters

- connectivity of the graph resulting after the direct key establishment phase is crucial
- a result from random graph theory [Erdős-Rényi]:

  in order for a random graph to be connected with probability c (e.g., c = 0.9999), the expected degree d of the vertices should be:

$$d = \frac{n-1}{n}(\ln(n) - \ln(-\ln(c))) \qquad (1)$$

- in our case, $d = pn'$ (2), where p is the probability that two nodes have a common key in their key rings, and n' is the expected number of neighbors (for a given deployment density)
- p depends on the size k of the pool and the size m of the key ring

$$p = 1 - \frac{((k-m)!)^2}{k!(k-2m)!} \qquad (3)$$

- $c \xrightarrow{(1)} d \xrightarrow{(2)} p \xrightarrow{(3)} k, m$

Setting the parameters – an example

- number of nodes: n = 10000
- expected number of neighbors: n' = 40
- required probability of connectivity after direct key establishment: c = 0.9999

- using (1):
  required node degree after direct key establishment: d = 18.42
- using (2):
  required probability of sharing a key: p = 0.46
- using (3):
  appropriate key pool and key ring sizes:
  k = 100000, m = 250
  k = 10000, m = 75
  …

Qualitative analysis

- advantages:
  - parameters can be adopted to special requirements
  - no need for intensive computation
  - path key establishment have some overhead …
    - decryption and re-encryption at intermediate nodes
    - communication overhead
  - but simulation results show that paths are not very long (2-3 hops)
  - no assumption on topology
  - easy addition of new nodes

- disadvantages:
  - node capture affects the security of non-captured nodes too
    - if a node is captured, then its keys are compromised
    - these keys may be used by other nodes too
  - if a path key is established through captured nodes, then the path key is compromised
  - no authentication is provided

Conclusions

- it is possible to establish pairwise shared keys in ad hoc networks without a globally trusted third party
- mobility, secure side channels, and friends are helpful
- in sensor networks, we need different types of keys
- node keys, cluster keys, and network keys can be established relatively easily using the technique of key pre-loading and using already established link keys
- link keys can be established with the technique of random key pre-distribution

Security and Cooperation in Wireless Networks

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Secure routing

ad hoc network routing protocols;
attacks on routing;
countermeasures;
secured ad hoc network routing protocols;
the wormhole attack and its detection;

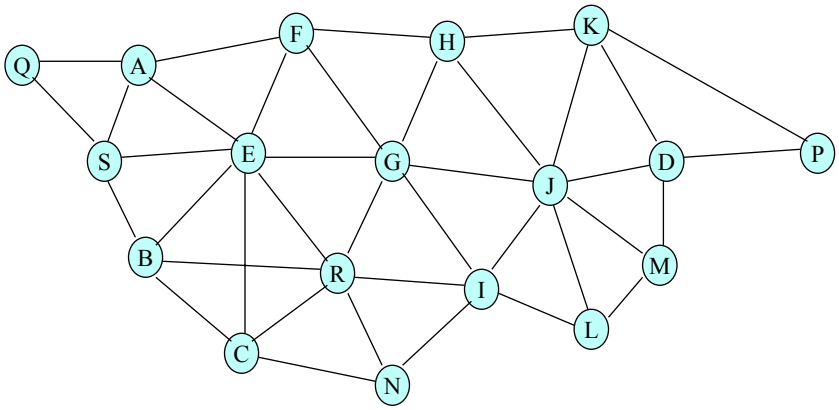
Ad hoc network routing protocols

- topology-based protocols
  - proactive
    - distance vector based (DSDV)
    - link-state (OLSR)
  - reactive (on-demand)
    - distance vector based (AODV)
    - source routing (DSR)
- position-based protocols
    - greedy forwarding (GPSR, GOAFR)
    - restricted directional flooding (DREAM, LAR)
- hybrid approaches

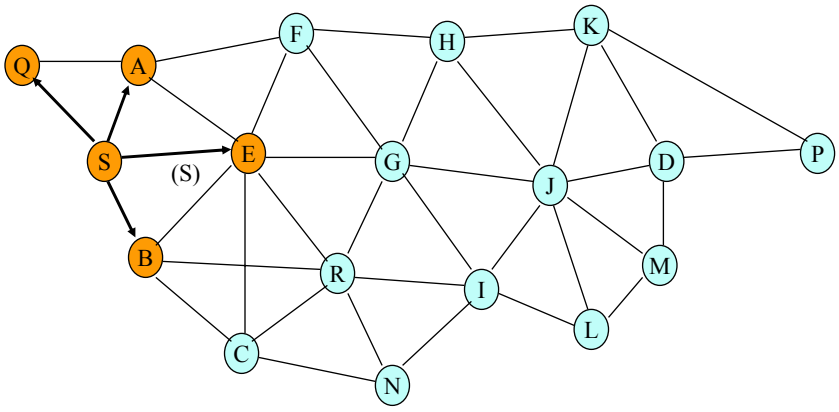
Example: Dynamic Source Routing (DSR)

- on-demand source routing protocol
- 2 components:
  - route discovery
    - used only when source S attempts to to send a packet to destination D
    - based on flooding of Route Requests (RREQ) and returning Route Replies (RREP)
  - route maintenance
    - makes S able to detect route errors (e.g., if a link along that route no longer works)

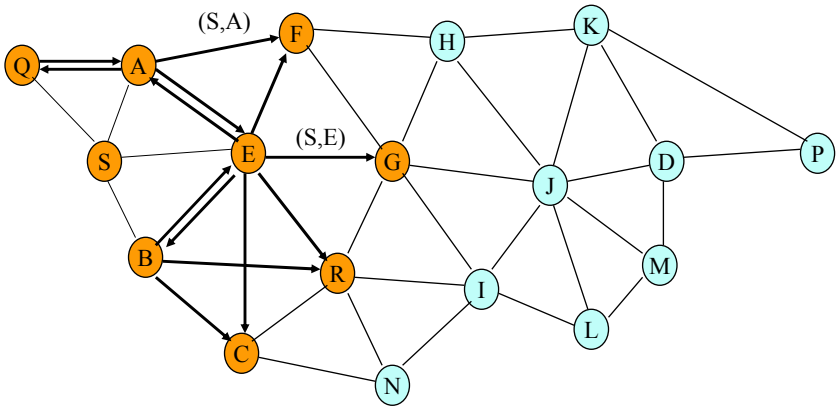
DSR: Route discovery (1)



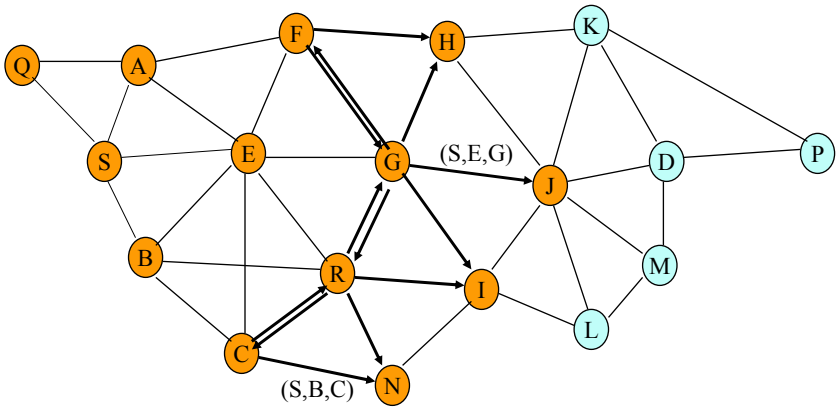
DSR: Route discovery (2)



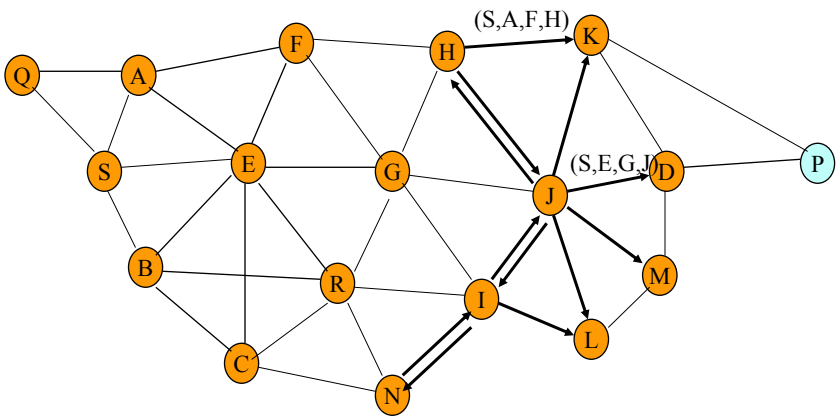
DSR: Route discovery (3)



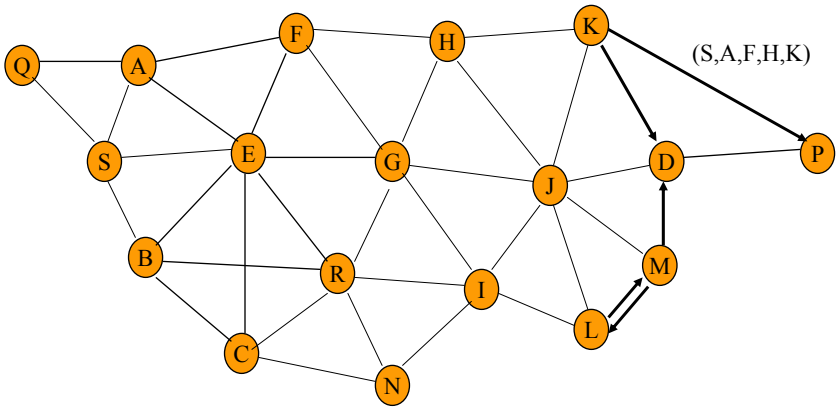
DSR: Route discovery (4)



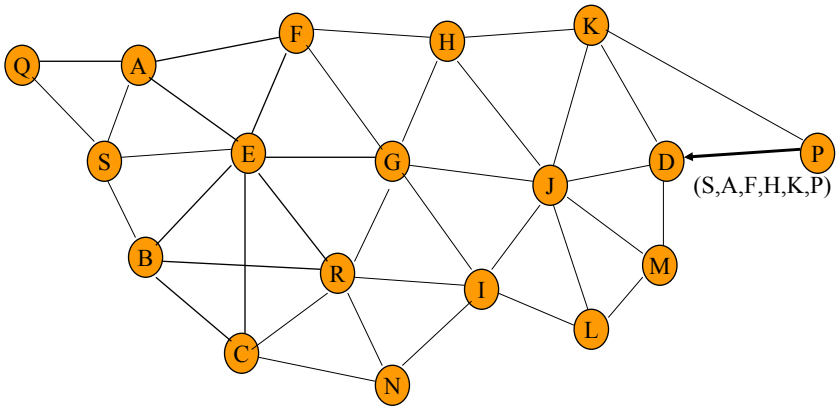
DSR: Route discovery (5)



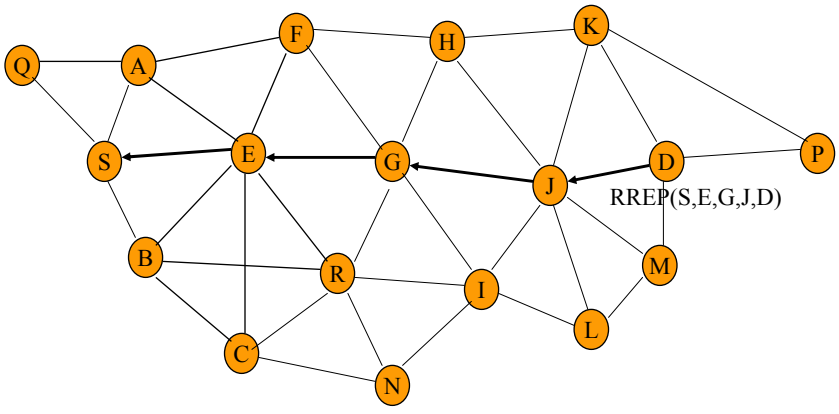
DSR: Route discovery (6)



DSR: Route discovery (7)



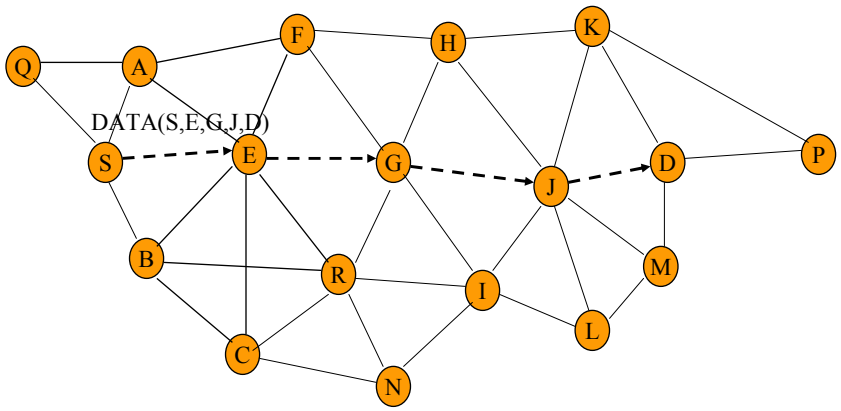
DSR: Route discovery (8)



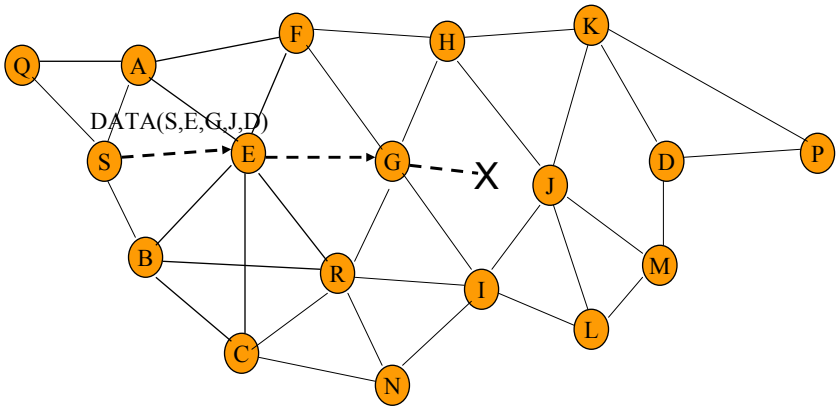
DSR: Route Discovery (9)

- Route reply by reversing the route (as illustrated) works only if all the links along the route are bidirectional
- If unidirectional links are allowed, then RREP may need a route discovery from D to S
- Note: IEEE 802.11 assumes that links are bidirectional

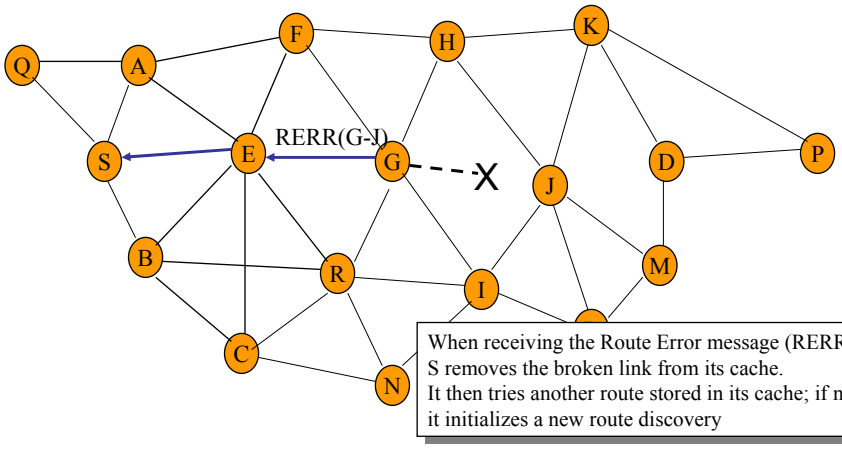
DSR: Data delivery



DSR: Route maintenance (1)



DSR: Route maintenance (2)



When receiving the Route Error message (RERR), S removes the broken link from its cache.
It then tries another route stored in its cache; if none, it initializes a new route discovery

DSR optimizations: route caching

- Principle: each node caches a new route it learns by any means
- Examples
  - When node S finds route (S, E, G, J, D) to D, it also learns route (S, E, G) to node G
  - In the same way, node E learns the route to D
  - Same phenomenon when transmitting route replies
- Moreover, routes can be overheard by nodes in the neighbourhood
- However, route caching has its downside: stale caches can severely hamper the performance of the network

Attacks on routing protocols (1/2)

- general objectives of attacks
  - increase adversarial control over the communications between some nodes;
  - degrade the quality of the service provided by the network;
  - increase the resource consumption of some nodes (e.g., CPU, memory, or energy).
- adversary model
  - insider adversary
    - can corrupt legitimate nodes
  - the attacker is not all-powerful
    - it is not physically present everywhere
    - it launches attacks from regular devices

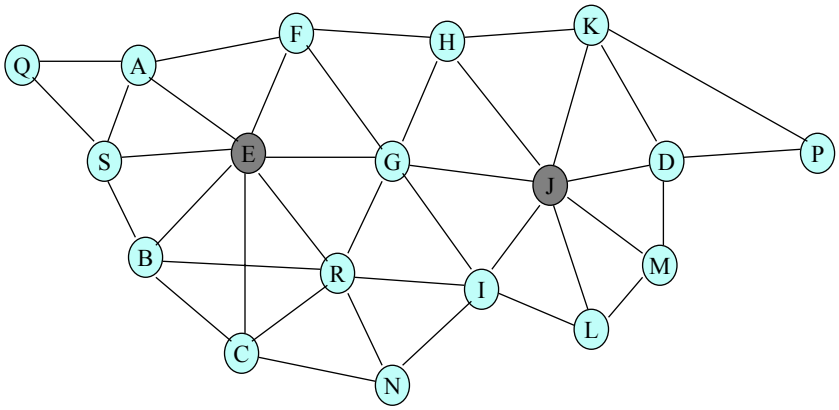
Attacks on routing protocols (2/2)

- attack mechanisms
  - eavesdropping, replaying, modifying, and deleting control packets
  - fabricating control packets containing fake routing information (forgery)
  - fabricating control packets under a fake identity (spoofing)
  - dropping data packets (attack against the forwarding function)
  - wormholes and tunneling
  - rushing
- types of attacks
  - route disruption
  - route diversion
  - creation of incorrect routing state
  - generation of extra control traffic
  - creation of a gray hole

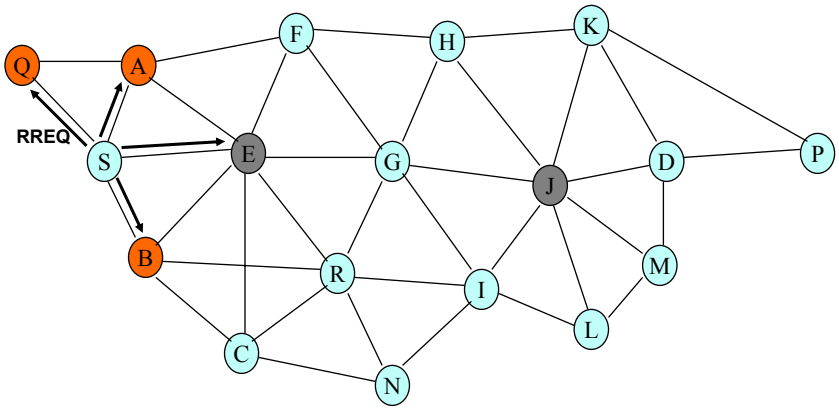
Route disruption

- the adversary prevents a route from being discovered between two nodes that are otherwise connected
- the primary objective of this attack is to degrade the quality of service provided by the network
  - the two victims cannot communicate, and
  - other nodes can also suffer and be coerced to use suboptimal routes
- attack mechanisms that can be used to mount this attack
  - dropping route request or route reply messages on a vertex cut
  - forging route error messages
  - combining wormhole/tunneling and control packet dropping
  - rushing

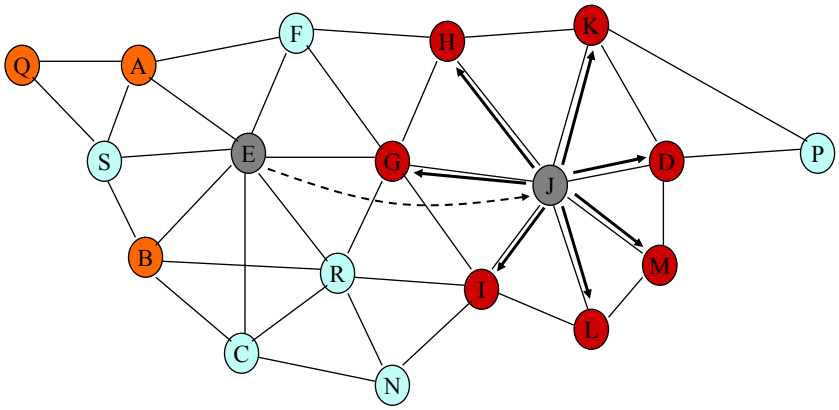
Example: Route disruption in DSR with rushing (1/6)



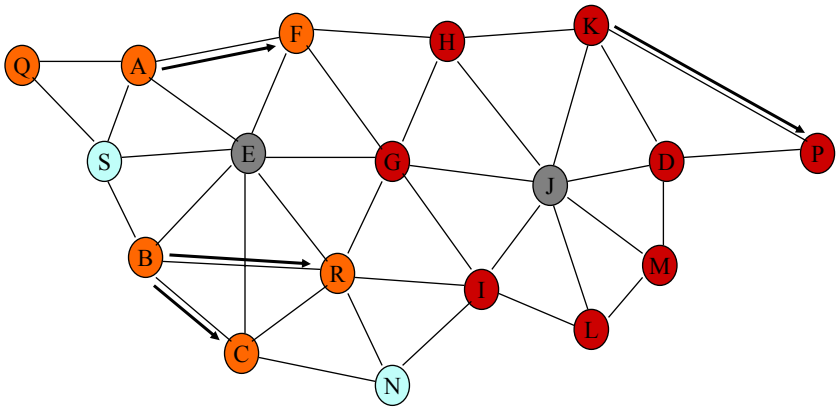
Example: Route disruption in DSR with rushing (2/6)



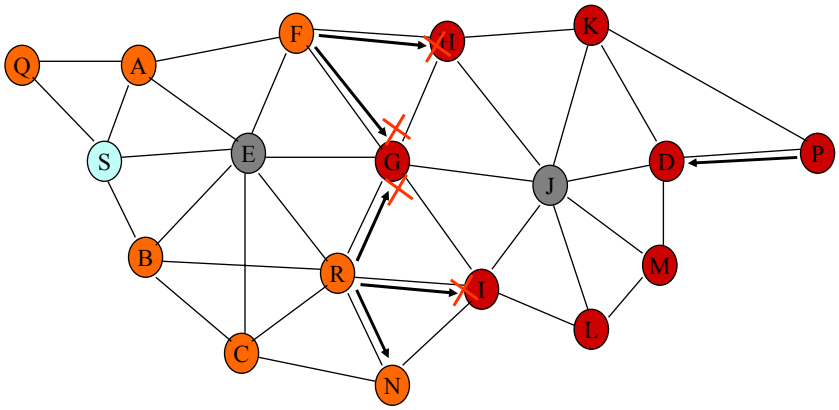
Example: Route disruption in DSR with rushing (3/6)



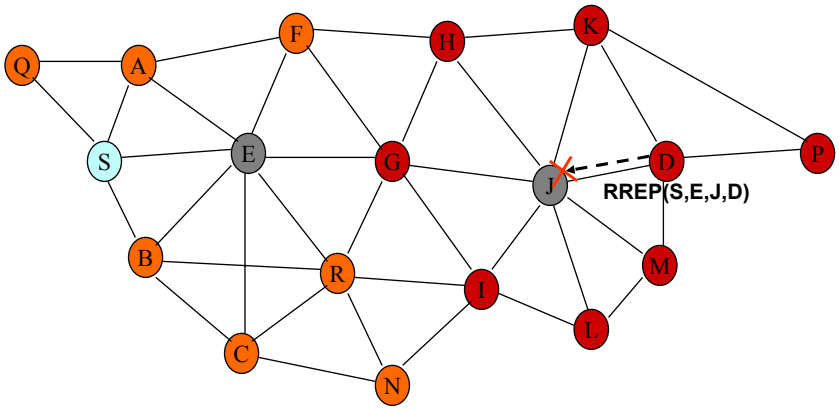
Example: Route disruption in DSR with rushing (4/6)



Example: Route disruption in DSR with rushing (5/6)



Example: Route disruption in DSR with rushing (6/6)



Route diversion

- due to the presence of the adversary, the protocol establishes routes that are different from those that it would establish, if the adversary did not interfere with the execution of the protocol
- the objective of route diversion can be
  - to increase adversarial control over the communications between some victim nodes
    - the adversary tries to achieve that the diverted routes contain one of the nodes that it controls or a link that it can observe
    - the adversary can eavesdrop or modify data sent between the victim nodes easier
  - to increase the resource consumption of some nodes
    - many routes are diverted towards a victim that becomes overloaded
  - degrade quality of service
    - by increasing the length of the discovered routes, and thereby, increasing the end-to-end delay between some nodes
- route diversion can be achieved by
  - forging or manipulating routing control messages
  - dropping routing control messages
  - setting up a wormhole/tunnel

Creation of incorrect routing state

- this attack aims at jeopardizing the routing state in some nodes so that the state appears to be correct but, in fact, it is not
  - data packets routed using that state will never reach their destinations
- the objective of creating incorrect routing state is
  - to increase the resource consumption of some nodes
    - the victims will use their incorrect state to forward data packets, until they learn that something goes wrong
  - to degrade the quality of service
- can be achieved by
  - spoofing, forging, modifying, or droppingcontrol packets

Generation of extra control traffic

- injecting spoofed control packets into the network
- aiming at increasing resource consumption due to the fact that such control packets are often flooded in the entire network

Setting up a gray hole

- an adversarial node selectively drops data packets that it should forward
- the objective is
  - to degrade the quality of service
    - packet delivery ratio between some nodes can decrease considerably
  - to increase resource consumption
    - wasting the resources of those nodes that forward the data packets that are finally dropped by the adversary
- implementation is trivial
  - adversarial node participates in the route establishment
  - when it receives data packets for forwarding, it drops them
  - even better if combined with wormhole/tunneling

Countermeasures

- origin authentication of control packets
  - using MACs or digital signatures
- protection of mutable information in control packets
  - often based on one-way hash functions
- detecting wormholes and tunnels
  - various mechanisms
- combating gray holes
  - using multi-path routing
  - using a "detect and react" approach

Example: Ariadne with standard MACs

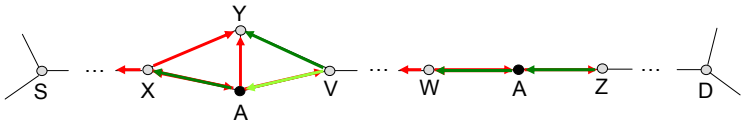
- Ariadne is a secured variant of DSR
- it uses control message authentication to prevent modification and forgery of routing messages
  - based on signatures, MACs, or TESLA
- it uses a per-hop hash mechanism to prevent the manipulation of the accumulated route information in the route request message

S	:	$h_S = MAC_{SD}(\text{rreq}, S, D, id)$
$S \rightarrow *$	:	$(\text{rreq}, S, D, id, h_S, [\,], [\,])$
F_1	:	$h_{F_1} = H(F_1, h_S)$
$F_1 \rightarrow *$	:	$(\text{rreq}, S, D, id, h_{F_1}, [F_1], [mac_{F_1}])$
F_2	:	$h_{F_2} = H(F_2, h_{F_1})$
$F_2 \rightarrow *$	:	$(\text{rreq}, S, D, id, h_{F_2}, [F_1, F_2], [mac_{F_1}, mac_{F_2}])$
$D \rightarrow F_2$	:	$(\text{rrep}, D, S, [F_1, F_2], mac_D)$
$F_2 \rightarrow F_1$	:	$(\text{rrep}, D, S, [F_1, F_2], mac_D)$
$F_1 \rightarrow S$	:	$(\text{rrep}, D, S, [F_1, F_2], mac_D)$

Other secure ad hoc network routing protocols

- SRP (on-demand source routing)
- SAODV (on-demand distance vector routing)
- ARAN (on-demand, routing metric is the propagation delay)
- SEAD (proactive distance vector routing)
- SMT (multi-path routing combined error correcting)
- Watchdog and Pathrater (implementation of the "detect and react" approach to defend against gray holes)
- ODSBR (source routing with gray hole detection)

An Active-1-2 attack on Ariadne



X → *: [rreq, S, D, *id*, h_X, (..., X), (..., mac_{XD})]
A → *: [rreq, S, D, *id*, *, (..., X, A), (..., mac_{XD}, h_X)]
... ...
W → *: [rreq, S, D, *id*, *, (..., X, A, V, ..., W), (..., mac_{XD}, h_X, ..., mac_{WD})]
A: h_A = H(A | h_X)
A → *: [rreq, S, D, *id*, h_A, (..., X, A), (..., mac_{XD}, mac_{AD})]
... ...
Z → A: [rrep, D, S, (..., X, A, Z, ...), mac_{DS}]
A → W: [rrep, D, S, (..., X, Y, V, ... W, A, ...), mac_{DS}]
... ...
V → Y: [rrep, D, S, (..., X, Y, V, ... W, A, ...), mac_{DS}]
A → X: [rrep, D, S, (..., X, A, Z, ...), mac_{DS}]
... ...
? → S: [rrep, D, S, (..., X, A, Z, ...), mac_{DS}] (a non-existent route!)

endairA

$S \rightarrow *$	:	$(\text{rreq}, S, D, id, [\,])$
$F_1 \rightarrow *$	:	$(\text{rreq}, S, D, id, [F_1])$
$F_2 \rightarrow *$	:	$(\text{rreq}, S, D, id, [F_1, F_2])$
$D \rightarrow F_2$	:	$(\text{rrep}, S, D, id, [F_1, F_2], [sig_D])$
$F_2 \rightarrow F_1$	:	$(\text{rrep}, S, D, id, [F_1, F_2], [sig_D, sig_{F_2}])$
$F_1 \rightarrow S$	:	$(\text{rrep}, S, D, id, [F_1, F_2], [sig_D, sig_{F_2}, sig_{F_1}])$

target verifies:
- there's no repeating ID in the node list
- last node in the node list is a neighbor

each intermediate node verifies:
- its own ID is in the node list
- there's no repeating ID in the node list
- next and previous nodes in the node list are neighbors
- all signatures are valid

source verifies:
- there's no repeating ID in the node list
- first node in the node list is a neighbor
- all signatures are valid

Properties of endairA

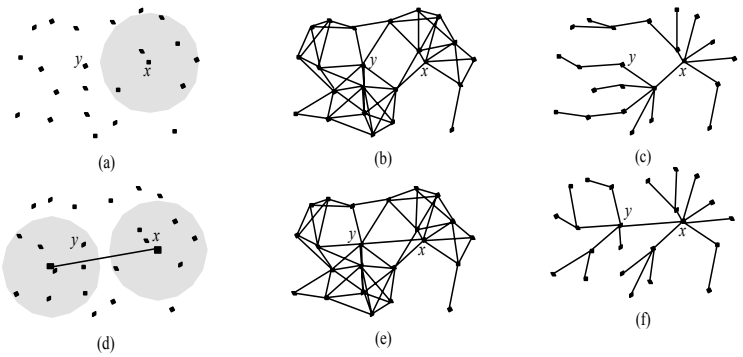
- security
  - endairA is provably secure if the signature scheme is secure against chosen message attacks
- efficiency
  - endairA requires less computation
    - route reply is signed and verified only by the nodes on the route
    - in Ariadne, route request is signed (and potentially verified) by every node in the network

The wormhole attack

- a wormhole is an out-of-band connection, controlled by the adversary, between two physical locations in the network
  - the adversary installs radio transceivers at both ends of the wormhole
  - it transfers packets (possibly selectively) received from the network at one end of the wormhole to the other end via the out-of-band connection, and re-injects the packets there into the network
- notes:
  - adversary's transceivers are not regular nodes (no node is compromised by the adversary)
  - adversary doesn't need to understand what it tunnels (e.g., encrypted packets can also be tunneled through the wormhole)
  - it is easy to mount a wormhole, but it may devastating effects on routing

Effects of a wormhole

- at the data link layer: distorted network topology



- at the network layer:
  - routing protocols may choose routes that contain wormhole links
    - typically those routes appear to be shorter
    - flooding based routing protocols (e.g., DSR, Ariadne) may not be able to discover other routes but only through the wormhole
  - adversary can then monitor traffic or drop packets (DoS)

Classification of wormhole detection methods

- centralized mechanisms
  - data collected from the local neighborhood of every node are sent to a central entity
  - based on the received data, a model of the entire network is constructed
  - the central entity tries to detect inconsistencies (potential indicators of wormholes) in this model
  - can be used in sensor networks, where the base station can play the role of the central entity
- decentralized mechanisms
  - each node constructs a model of its own neighborhood using locally collected data
  - each node tries to detect inconsistencies on its own
  - advantage: no need for a central entity (fits well some applications)
  - disadvantage: nodes need to be more complex

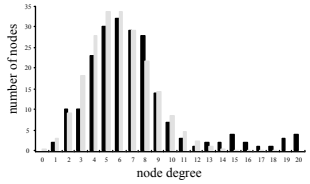
Statistical wormhole detection in sensor NWs

- each node reports its list of believed neighbors to the base station
- the base station reconstructs the connectivity graph (model)
- *a wormhole always increases the number of edges* in the connectivity graph
- this increase may change the properties of the connectivity graph in a detectable way (anomaly)
- detection can be based on statistical hypothesis testing methods (e.g. the χ^2-test)

Two examples

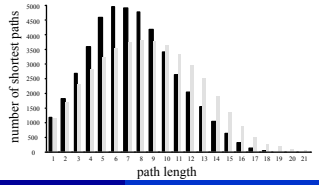
- a wormhole that creates many new edges may increase the *number of neighbors* of the affected nodes

→ distribution of node degrees will be distorted



- a wormhole is usually a shortcut that decreases the length of the shortest paths in the network

→ distribution of the length of the shortest paths will be distorted



Packet leashes

- packet leashes ensure that packets are not accepted "too far" from their source
- geographical leashes
  - each node is equipped with a GPS receiver
  - when sending a packet, the node puts its GPS position into the header
  - the receiving node verifies if the sender is really within communication range
- temporal leashes
  - nodes' clocks are very tightly synchronized
  - when sending a packet, the node puts a timestamp in the header
  - the receiving node estimates the distance of the sender based on the elapsed time and the speed of light

$$d_{est} < v_{light}(t_{rcv} - t_{snd} + \Delta_t)$$

  - note: $v_{light}\,\Delta_t$ must be much smaller than the communication range

Conclusions

- routing is a fundamental function in networking, hence, an ideal target for attacks
- attacks against routing aim at
  - increasing adversarial control over the communications between some nodes;
  - degrading the quality of the service provided by the network;
  - increasing the resource consumption of some nodes (e.g., CPU, memory, or energy)
- many attacks (but not all!) can be prevented by authenticating routing control messages
- it is difficult to protect the mutable parts of control messages
- special attacks (e.g., wormholes and rushing) needs special protection mechanisms
- several secured ad hoc network routing protocols have been proposed
- some of them have weaknesses that are exploitable by attacks

Outline

- New wireless networks and new challenges (20')
- Thwarting malicious behavior
  - introduction to cryptography and security techniques (25')
  - naming and addressing (20')
  - key establishment (20')
  - secure routing (30')
- Thwarting selfish behavior
  - introduction to game theory (25')
  - selfishness in packet forwarding (20')
  - border games in cellular networks (20')

Security and Cooperation in Wireless Networks

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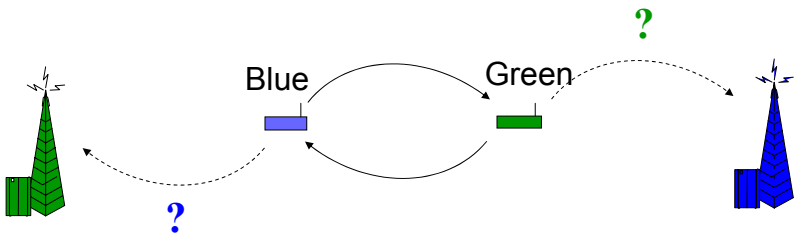
Introduction to game theory

strategic form games;
solution concepts:
- strict dominance
- weak dominance
- Nash equilibrium;
Pareto optimality;
repeated games;

What is game theory?

- Discipline aiming at modeling situations in which actors have to make decisions which have mutual, **possibly conflicting**, consequences
- Classical applications: **economics**, but also politics and biology
- Example: should a company invest in a new plant, or enter a new market, considering that the **competition** *may* make similar moves?
- Most widespread kind of game: **non-cooperative** (meaning that the players do not attempt to find an agreement about their possible moves)

Example 1: The Forwarder's Dilemma



E1: From a problem to a game

- users controlling the devices are ***rational*** = try to maximize their benefit
- game formulation: G = (P,S,U)
  - P: set of players
  - S: set of strategy functions
  - U: set of utility functions

→ • Reward for packet reaching the destination: 1
• Cost of packet forwarding: c (0 < c << 1)

- ***strategic-form*** representation

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

Solving the Forwarder's Dilemma (1/2)

Strict dominance: strictly best strategy, for any strategy of the other player(s)

Strategy s_i strictly dominates if

$$u_i(s_i', s_{-i}) < u_i(s_i, s_{-i}), \forall s_{-i} \in S_{-i}, \forall s_i' \in S_i$$

where: $u_i \in U$ utility function of player *i*

$s_{-i} \in S_{-i}$ strategies of all players except player i

In Example 1, strategy Drop ***strictly dominates*** strategy Forward

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

Solving the Forwarder's Dilemma (2/2)

Solution by iterative strict dominance:

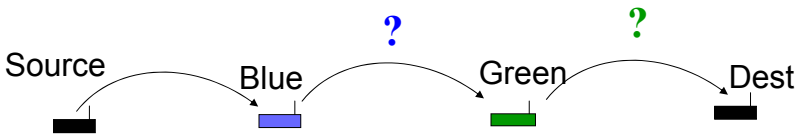
Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

BUT Drop ***strictly dominates*** Forward

Forward would result in a ***better outcome*** } Dilemma

Result: Tragedy of the commons ! (Hardin, 1968)

Example 2: The Joint Packet Forwarding Game



- Reward for packet reaching the destination: 1
- Cost of packet forwarding: c (0 < c << 1)

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 0)
Drop	(0, 0)	(0, 0)

No strictly dominated strategies !

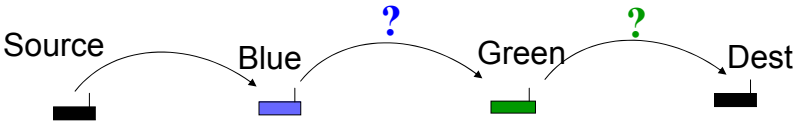
E2: Weak dominance

Weak dominance: strictly better strategy for at least one opponent strategy

Strategy s'_i is weakly dominated by strategy s_i if

$$u_i(s_i', s_{-i}) \leq u_i(s_i, s_{-i}), \forall s_{-i} \in S_{-i}$$

with strict inequality for at least one s_{-i}



Iterative weak dominance

BUT

The result of the iterative weak dominance is not unique in general !

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 0)
Drop	(0, 0)	(0, 0)

Nash equilibrium (1/2)

Nash Equilibrium: no player can increase its utility by deviating unilaterally

E1: The Forwarder's Dilemma

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

E2: The Joint Packet Forwarding game

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 0)
Drop	(0, 0)	(0, 0)

Nash equilibrium (2/2)

Strategy profile s^* constitutes a **Nash equilibrium** if, for each player *i*,

$$u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*), \forall s_i \in S_i$$

where: $u_i \in U$ utility function of player i

$s_i \in S_i$ strategy of player i

The **best response** of player *i* to the profile of strategies s_{-i} is a strategy s_i such that:

$$b_i(s_{-i}) = \arg\max_{s_i \in S_i} u_i(s_i, s_{-i})$$

Nash Equilibrium = Mutual best responses

Caution! Many games have more than one Nash equilibrium

Efficiency of Nash equilibria

E2: The Joint Packet Forwarding game

Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 0)
Drop	(0, 0)	(0, 0)

How to choose between several Nash equilibria ?

Pareto-optimality: A strategy profile is Pareto-optimal if it is not possible to increase the payoff of any player without decreasing the payoff of another player.

Repeated games

- repeated interaction between the players (in stages)
- move: decision in one interaction
- strategy: defines how to choose the next move, given the previous moves
- history: the ordered set of moves in previous stages
  - most prominent games are history-1 games (players consider only the previous stage)
- initial move: the first move with no history
- finite-horizon vs. infinite-horizon games
- stages denoted by t (or k)

Utilities in repeated games

- finite-horizon vs. infinite-horizon games
- myopic vs. long-sighted repeated game

myopic: $\overline{u}_i = u_i(t+1)$

long-sighted finite: $\overline{u}_i = \sum_{t=0}^{T} u_i(t)$

long-sighted infinite: $\overline{u}_i = \sum_{t=0}^{\infty} u_i(t)$

utility with discounting: $\overline{u}_i = \sum_{t=0}^{\infty} u_i(t) \cdot \omega^t$

$0 < \omega \leq 1$ is the discounting factor

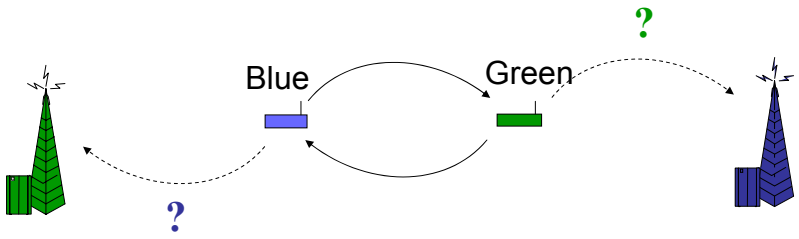
Strategies in repeated games

- usually, history-1 strategies, based on different inputs:
  - others' behavior: $m_i(t+1) = s_i\left[m_{-i}(t)\right]$
  - others' and own behavior: $m_i(t+1) = s_i\left[m_i(t), m_{-i}(t)\right]$
  - utility: $m_i(t+1) = s_i\left[u_i(t)\right]$

Example strategies in the Forwarder's Dilemma:

Blue (t)	initial move	F	D	strategy name
Green (t+1)	F	F	F	AllC
	F	F	D	Tit-For-Tat (TFT)
	D	D	D	AllD
	F	D	F	Anti-TFT

The Repeated Forwarder's Dilemma



Blue \ Green	Forward	Drop
Forward	(1-c, 1-c)	(-c, 1)
Drop	(1, -c)	(0, 0)

stage payoff

Analysis of the Repeated Forwarder's Dilemma (1/3)

infinite game with discounting: $\overline{u}_i = \sum_{t=0}^{\infty} u_i(t) \cdot \omega^t$

Blue strategy	Green strategy
AllD	AllD
AllD	TFT
AllD	AllC
AllC	AllC
AllC	TFT
TFT	TFT

Blue utility	Green utility
0	0
1	-c
1/(1-ω)	-c/(1-ω)
(1-c)/(1-ω)	(1-c)/(1-ω)
(1-c)/(1-ω)	(1-c)/(1-ω)
(1-c)/(1-ω)	(1-c)/(1-ω)

Analysis of the Repeated Forwarder's Dilemma (2/3)

Blue strategy	Green strategy	Blue utility	Green utility
AllD	AllD	0	0
AllD	TFT	1	-c
AllD	AllC	1/(1-ω)	-c/(1-ω)
AllC	AllC	(1-c)/(1-ω)	(1-c)/(1-ω)
AllC	TFT	(1-c)/(1-ω)	(1-c)/(1-ω)
TFT	TFT	(1-c)/(1-ω)	(1-c)/(1-ω)

- AllC receives a high payoff with itself and TFT, but
- AllD exploits AllC
- AllD performs poor with itself
- TFT performs well with AllC and itself, and
- TFT retaliates the defection of AllD

TFT is the best strategy if ω is high !

Analysis of the Repeated Forwarder's Dilemma (3/3)

Blue strategy	Green strategy	Blue utility	Green utility
AllD	AllD	0	0
TFT	TFT	(1-c)/(1-ω)	(1-c)/(1-ω)

Theorem: In the Repeated Forwarder's Dilemma, if both players play AllD, it is a Nash equilibrium.

Theorem: In the Repeated Forwarder's Dilemma, both players playing TFT is a Nash equilibrium $c < \omega$.

The Nash equilibrium s_{Blue} = TFT and s_{Green} = TFT is Pareto-optimal (but s_{Blue} = AllD and s_{Green} = AllD is not) !

Conclusions

- Game theory can help modeling greedy behavior in wireless networks
- Discipline still in its infancy
- Alternative solutions
  - Ignore the problem
  - Build protocols in tamper-resistant hardware

Security and Cooperation in Wireless Networks

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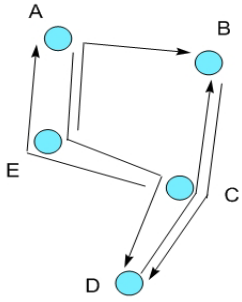
Selfishness in packet forwarding

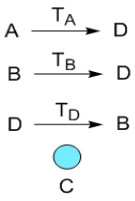
Introduction

- the operation of multi-hop wireless networks requires the nodes to forward data packets on behalf of other nodes
- however, such cooperative behavior has no direct benefit for the forwarding node, and it consumes valuable resources (battery)
- hence, the nodes may tend to behave selfishly and deny cooperation
- if many nodes defect, then the operation of the entire network is jeopardized
- questions:
  - What are the conditions for the emergence of cooperation in packet forwarding?
  - Can it emerge spontaneously or should it be stimulated by some external mechanism?

Modeling packet forwarding as a game

Players: nodes





Strategy:
cooperation level

Payoff (of node i):
proportion of packets sent by node i reaching their destination

Cost function

Cost for forwarder f_j:

$$\eta_{f_j}(r,t) = -T_s(r) \cdot c \cdot \hat{\tau}_j(r,t)$$

where:

$T_s(r)$ – traffic sent by source s on route r
c – unit cost of forwarding

Example :

$$\hat{\tau}_C(r,t) = \prod_{k \in \{E,C\}} p_{f_k}(t) = p_E(t) \cdot p_C(t)$$

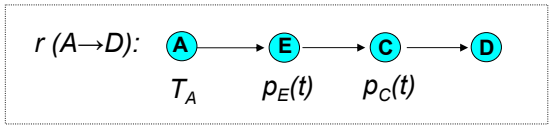
$$\eta_C(r,t) = -T_A(r) \cdot c \cdot \hat{\tau}_j(r,t)$$

Normalized throughput at forwarder f_j:

$$\hat{\tau}_j(r,t) = \prod_{k=1}^{j} p_{f_k}(t)$$

where:

r – route on which f_k is a forwarder
t – time slot
f_k – forwarders on route r
p_{fk} – cooperation level of forwarder f_k



Utility function

Experienced throughput :

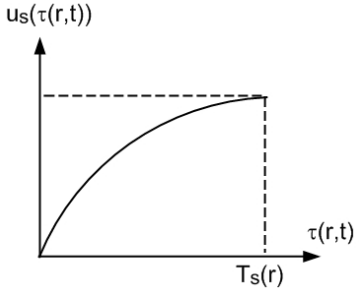
$$\tau(r,t) = T_s(r) \cdot \prod_{k=1}^{l} p_{f_k}(t)$$

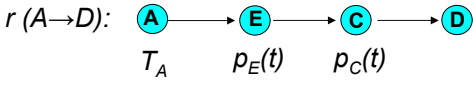
where: s – source
r – route on which s is a source
t – time slot
f_k – forwarders for s
p_{fk} – cooperation level of forwarder f_k

Example :

$$\tau(r,t) = T_A(r) \cdot p_E(t) \cdot p_C(t)$$

Utility function :





Total payoff

Payoff = Utility - Cost

$$\pi_i(t) = \sum_{q \in S_i(t)} u_i\left(\tau(q,t)\right) + \sum_{r \in F_i(t)} \eta_i(r,t)$$

where: $S_i(t)$ – set of routes on which i is a source
$F_i(t)$ – set of routes on which i is a forwarder

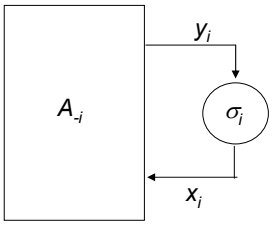
The goal of each node is to maximize its total payoff over the game

$$\max \bar{\pi}_i = \sum_{t=0}^{\infty} \pi_i(t) \cdot \omega^t$$

where: ω – discounting factor
t – time

Example :

Representation of the nodes as players



Node i is playing against the rest of the network (represented by the box denoted by A_{-i})

Strategy function for node i:

$$p_i(t) = \sigma_i\left(\left[\tau(r,t-1)\right]_{r \in S_i(t-1)}\right)$$

where:

$\tau(r,t)$ – experienced throughput
S_i – set of routes on which i is a source

Examples of strategies

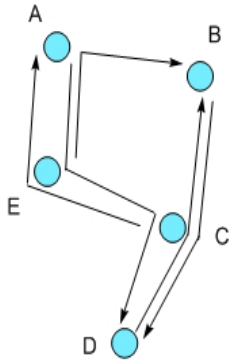
Strategy	Initial cooperation level	Function $\sigma_i(y_i)=x_i$
AllD (always defect)	0	$\sigma_i(y_i)=0$
AllC (always cooperate)	1	$\sigma_i(y_i)=1$
TFT (Tit-For-Tat)	1	$\sigma_i(y_i)=y_i$

where y_i stands for the input

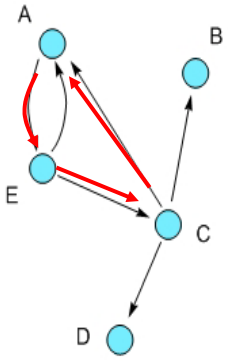
- **non-reactive strategies**:
  the output of the strategy function
  is independent of the input (example: AllD and AllC)
- **reactive strategies**:
  the output of the strategy function
  depends on the input (example: TFT)

Concept of dependency graph

dependency: the benefit of each source is dependent on the behavior of its forwarders



(a) routes



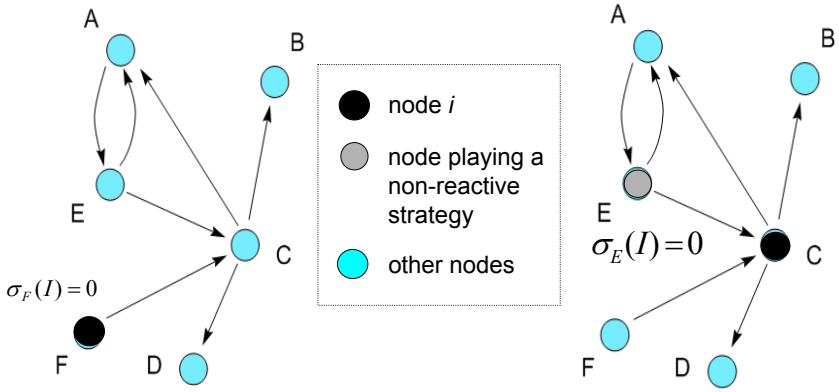
(b) dependency graph

dependency loop

Analytical Results (1/2)

Theorem 1: If node *i* does not have any dependency loops, then its best strategy is AllD.

Theorem 2: If node *i* has only non-reactive dependency loops, then its best strategy is AllD.



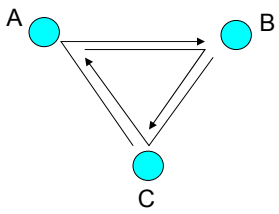
Corollary 1: If every node plays AllD, it is a Nash-equilibrium.

Analytical results (2/2)

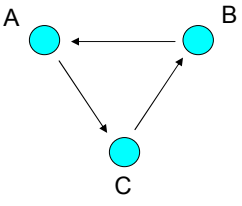
Theorem 3 (simplified): Assuming that node *i* is a forwarder, its behavior will be cooperative only if it has a dependency loop with each of its sources

Corollary 2: If Theorem 3 holds for every node, it is a Nash-equilibrium.

Example in which Corollary 2 holds:

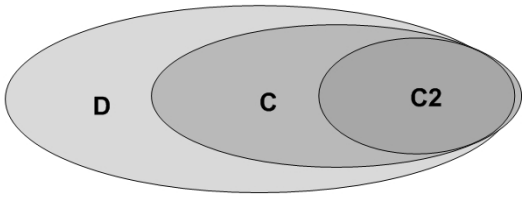


Network



Dependency graph

Classification of scenarios



D: Set of scenarios, in which every node playing AllD is a Nash equilibrium

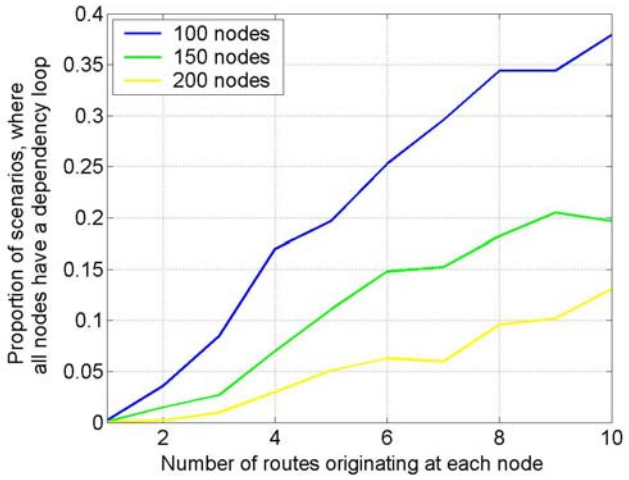
C: Set of scenarios, in which a Nash equilibrium based on cooperation is not excluded by Theorem 1

C2: Set of scenarios, in which cooperation is based on the conditions expressed in Corollary 2

Simulation settings

Number of nodes	100, 150, 200
Distribution of the nodes	random uniform
Area type	torus
Area size	1500x1500m, 1850x1850m, 2150x2150m
Radio range	200 m
Number of routes originating at each node	1-10
Route selection	shortest path
Number of simulation runs	1000

Simulation results



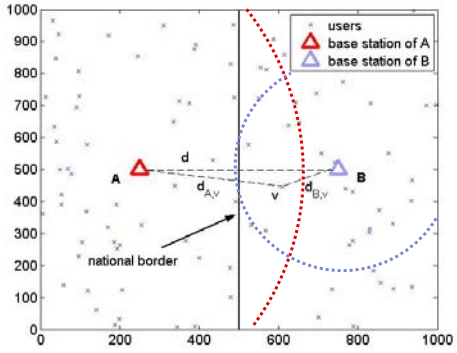
Conclusions

- Analytical results:
  - If everyone drops all packets, it is a Nash-equilibrium
  - **In theory**, given some conditions, a cooperative Nash-equilibrium can exist (i.e., each forwarder forwards all packets)
- Simulation results:
  - **In practice**, the conditions for cooperative Nash-equilibria are very restrictive : the likelihood that the conditions for cooperation hold for every node is extremely small
- Consequences:
  - Cooperation cannot be taken for granted
  - Mechanisms that stimulate cooperation are necessary
    - incentives based on virtual currency
    - reputation systems

Border games in cellular networks

Introduction

- spectrum licenses do not regulate access over national borders
- adjust pilot power to attract more users



Is there an incentive for operators to apply competitive pilot power control?

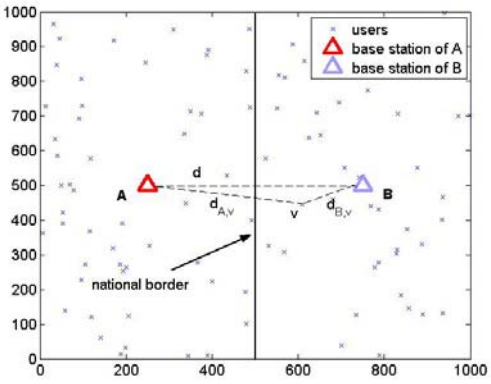
System model (1/2)

Network:

- cellular networks using CDMA
  - channels defined by orthogonal codes
- two operators: A and B
- one base station each
- pilot signal power control

Users:

- roaming users
- users uniformly distributed
- select the best quality BS
- selection based signal-to-interference-plus-noise ratio (*SINR*)



System model (2/2)

pilot signal *SINR*:

$$SINR_{iv}^{pilot} = \frac{G_p^{pilot} \cdot P_i \cdot g_{iv}}{N_0 \cdot \mathrm{W} + I_{own}^{pilot} + I_{other}^{pilot}}$$

$$I_{own}^{pilot} = \varsigma \cdot g_{iv} \cdot \left(\sum_{w \in \mathrm{M}_i} T_{iw} \right)$$

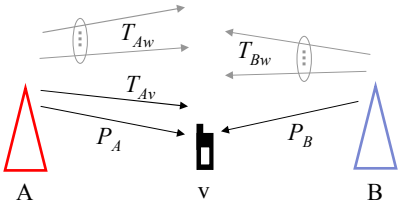
$$I_{other}^{pilot} = \eta \cdot \sum_{j \neq i} g_{jv} \cdot \left(P_j + \sum_{w \in \mathrm{M}_i} T_{iw} \right)$$

traffic signal *SINR*:

$$SINR_{iv}^{tr} = \frac{G_p^{tr} \cdot T_{iv} \cdot g_{iv}}{N_0 \cdot \mathrm{W} + I_{own}^{tr} + I_{other}^{tr}}$$

$$I_{own}^{pilot} = \varsigma \cdot g_{iv} \cdot \left(P_i + \sum_{w \neq v, w \in \mathrm{M}_i} T_{iw} \right)$$

$$I_{other}^{tr} = I_{other}^{pilot}$$



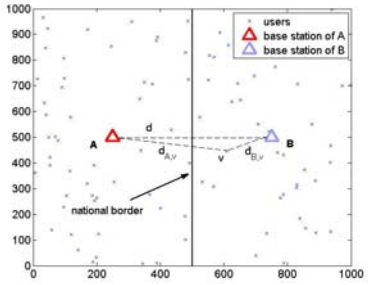
P_i – pilot power of i
G_p^{pilot} – processing gain for the pilot signal
g_{iv} – channel gain between BS i and user v
N_0 – noise energy per symbol
W – available bandwidth
I_{own}^{pilot} – own-cell interference affecting the pilot signal
ς – own-cell interference factor
T_{iv} – traffic power between BS i and user v
M_i – set of users attached to BS i
η – other-to-own-cell interference factor

Game-theoretic model

- Power Control Game, G_{PC}
  - players → networks operators (BSs), A and B
  - strategy → pilot signal power, 0W < P_i < 10W, i = {A, B}
  - standard power, P^S = 2W
  - payoff → profit, $u_i = \sum_{v \in M_i} \theta_v$ where θ_v is the expected income serving user v
  - normalized payoff difference:

$$\Delta_i = \frac{\max_{s_i} \left(u_i \left(s_i, P^S \right) - u_i \left(P^S, P^S \right) \right)}{u_i \left(P^S, P^S \right)}$$

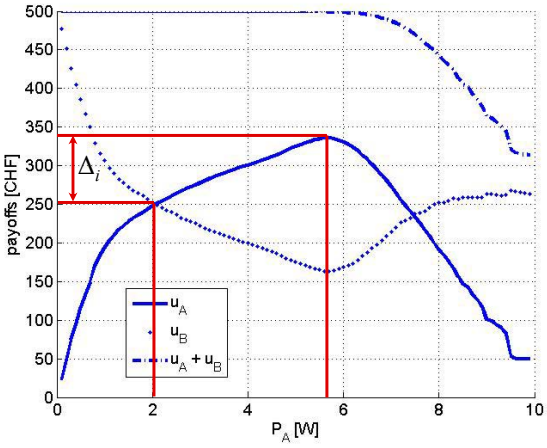
Simulation settings



Parameter	*Value*
simulation area size	1 km^2
BS positions	(250 m, 500 m) and (750 m, 500 m)
default distance between BSs, d	500 m
user distribution	random uniform
number of simulations	500
default path loss exponent, α	4
BS max power	43 dBm = 20 W
BS max load	40 dBm = 10 W
BS standard power, P^s	33 dBm = 2 W
BS min power	20 dBm = 0.1 W
power control step size, P_{step}	0.1 W
orthogonality factor, ζ	0.4
other-to-own-cell interference factor, η	0.4
user traffic types:	audio, $\mathbb{R}^{tr}$ = 12.2 kbps
	video, $\mathbb{R}^{tr}$ = 144 kbps
	data, $\mathbb{R}^{tr}$ = 384 kbps
required CIR (audio, video, data):	-20 dB, -12.8 dB, -9 dB
expected incomes (θ_{audio}, θ_{video}, θ_{data}):	10, 20, 50 CHF/month

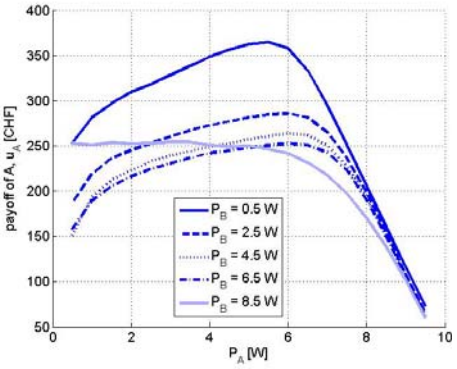
Is there a game?

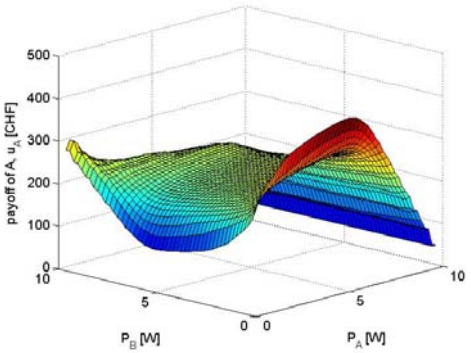
- only A is strategic (B uses $P_B = P^S$)
- 10 data users
- path loss exponent, $\alpha = 2$



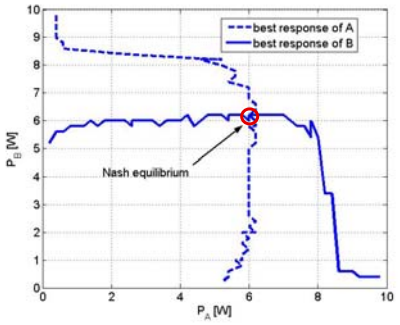
When both operators are strategic

- 10 data users
- path loss exponent, $\alpha = 4$

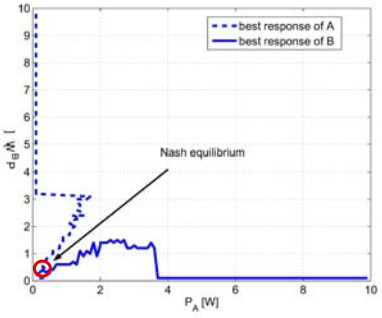




Nash equilibria



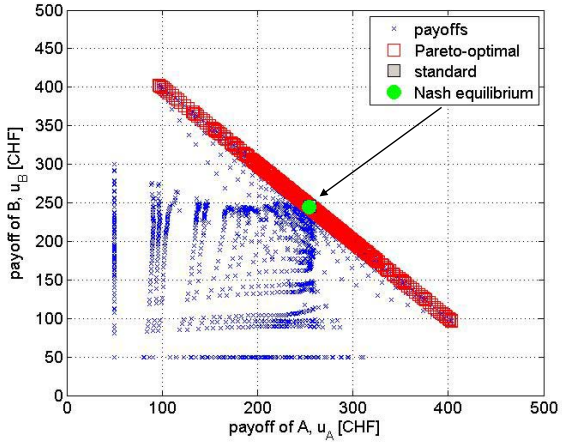
10 data users



100 data users

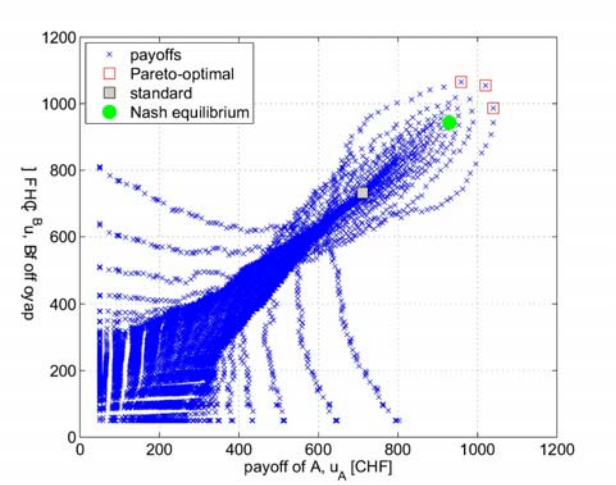
Efficiency (1/2)

- 10 data users



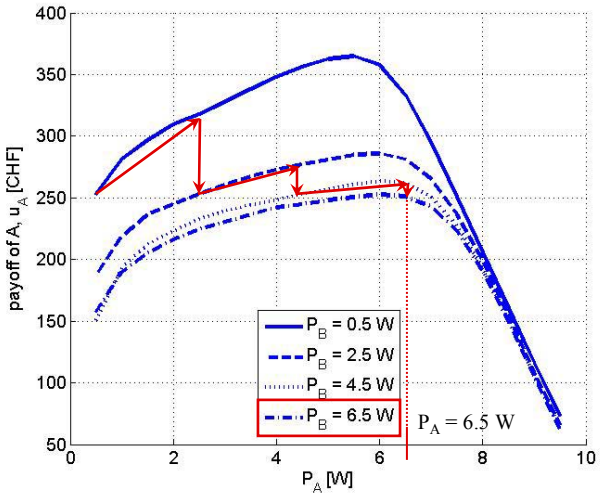
Efficiency (2/2)

- 100 data users



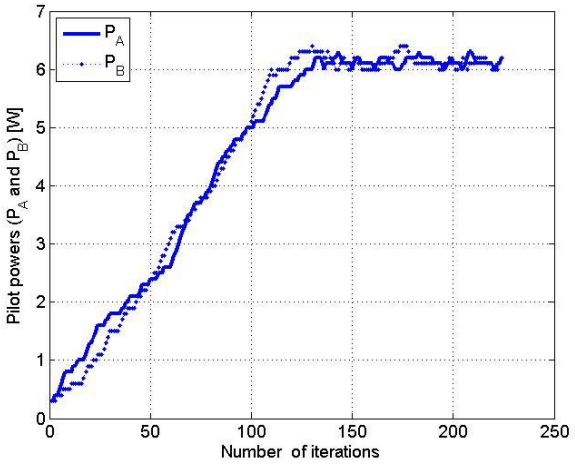
Convergence to NE (1/2)

- convergence based on better-response dynamics
- convergence step: 2 W



Convergence to NE (2/2)

- convergence step: 0.1 W



Conclusions

- not only individual nodes may exhibit selfish behavior, but operators can be selfish too
- example: adjusting pilot power to attract more users at national borders
- the problem can be modeled as a game between the operators
  - the game has an efficient Nash equilibrium
  - there's a simple convergence algorithm that drives the system into the Nash equilibrium

A textbook

- written by
  - Levente Buttyan (BME)
  - Jean-Pierre Hubaux (EPFL)
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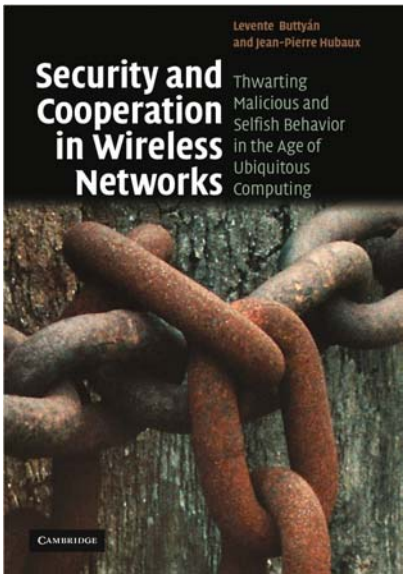

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