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Opportunistic Communication in Disconnected Mobile Ad Hoc Networks

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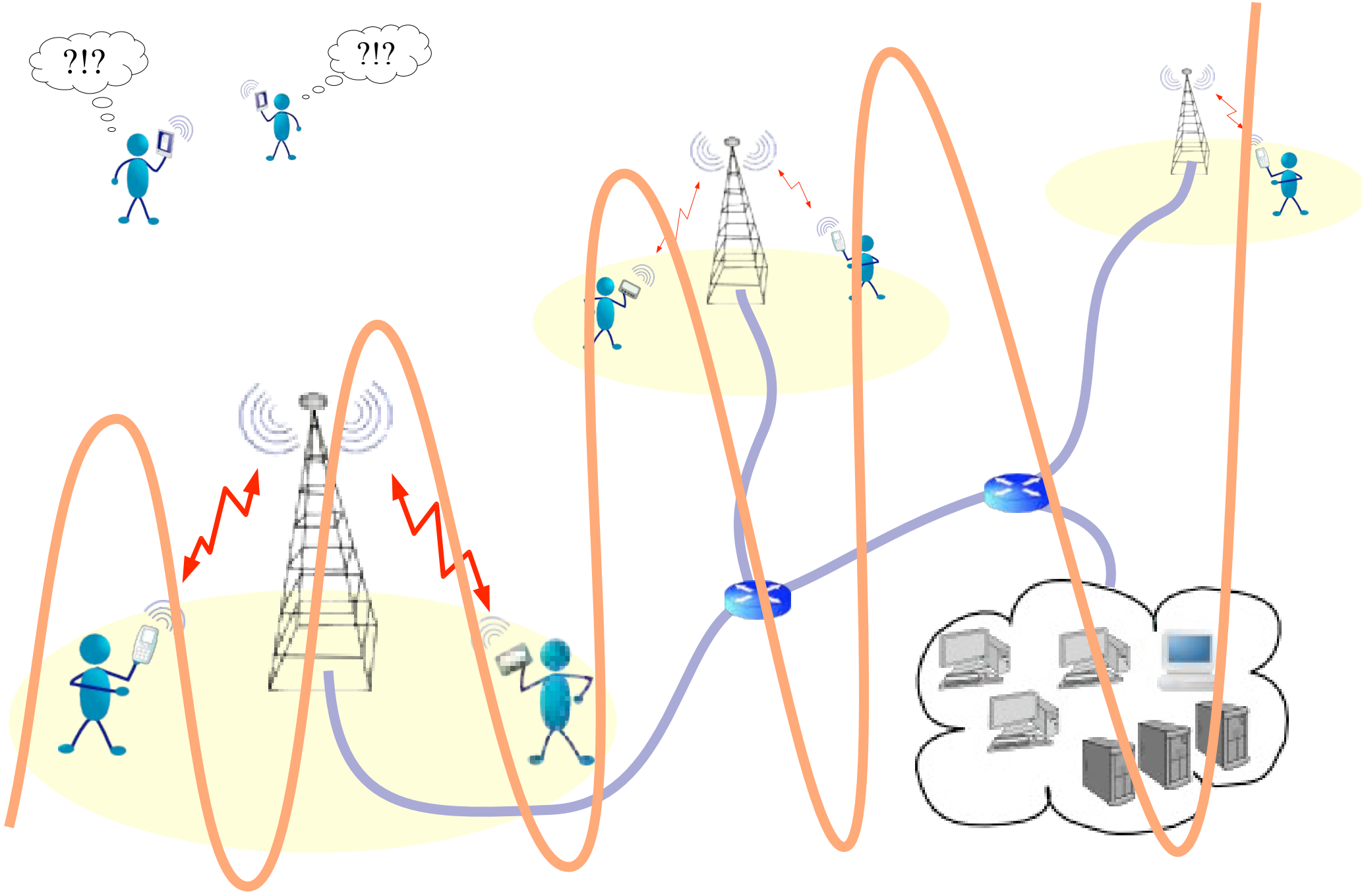
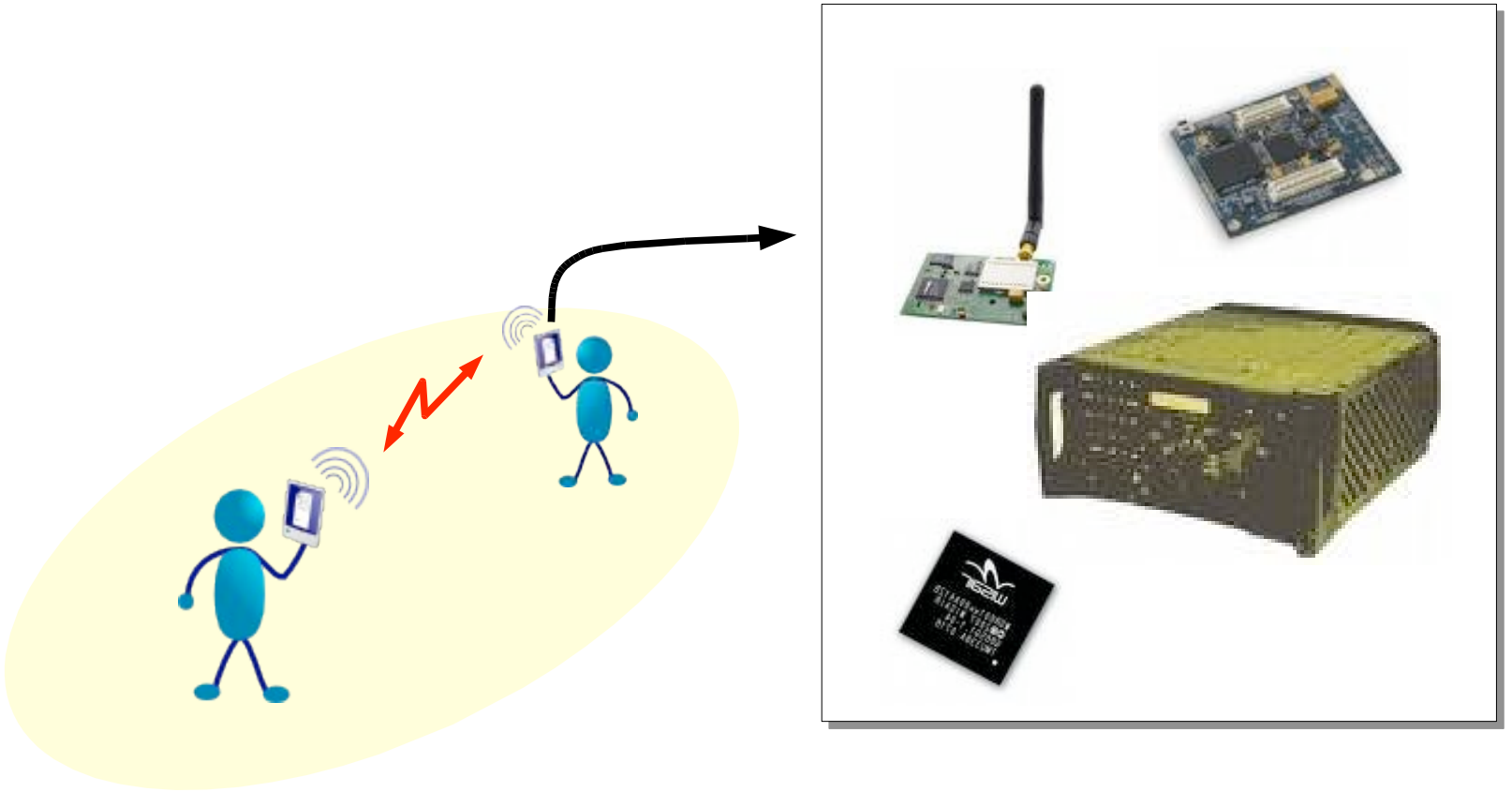
Overview of this talk

- Ad hoc networking vs infrastructure-based networking
- The problem with disconnected MANETs
- Delay-tolerant networking: from inter-planetary networking to mobile ad hoc networking
- Opportunistic, delay-tolerant communication in disconnected MANETs
- Possible application fields
- Objectives and challenges
- A (partial) survey of routing methods (custody transfer, epidemy, spray & wait, socially-aware routing, etc.)
- Content-based networking in disconnected MANETs
- Software applications
- Beyond human-to-human communication
- Considerations about security and incentives
- Conclusion

Mobile communication?...

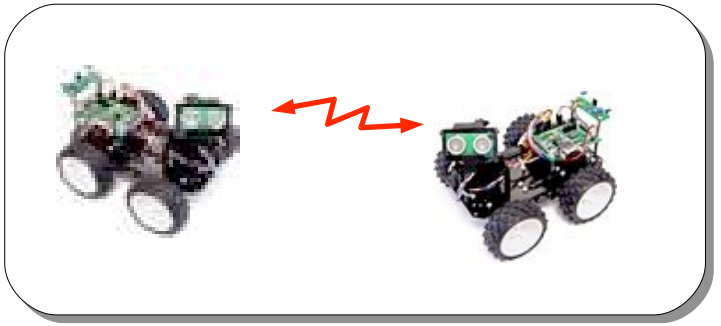


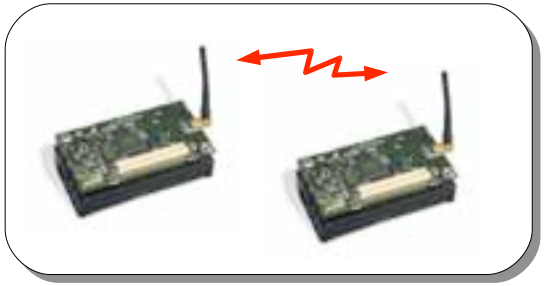
Mobile ad hoc networking

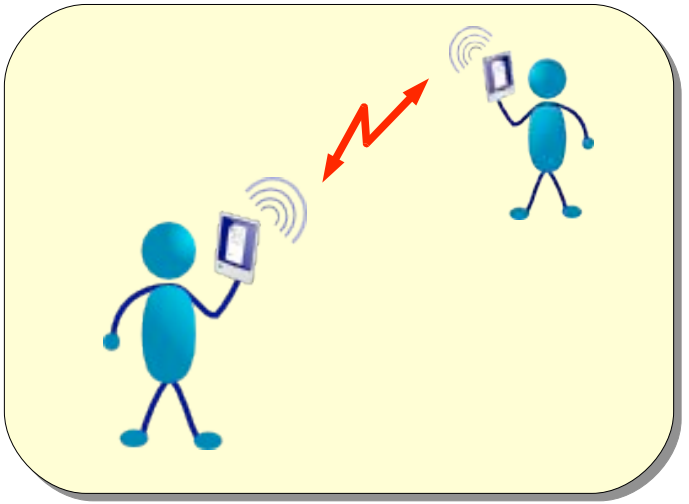


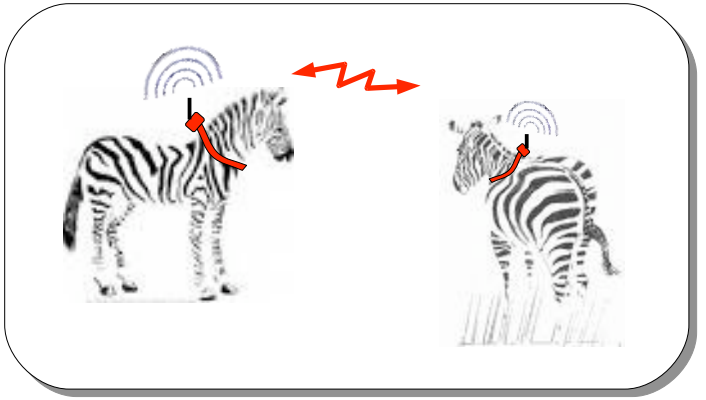
- **Enabling technologies for ad hoc communication**
  - **IEEE 802.11 (Wi-Fi in ad hoc mode)**
  - **IEEE 802.15 (Bluetooth, ZigBee...)**
  - **PR4G, etc.**

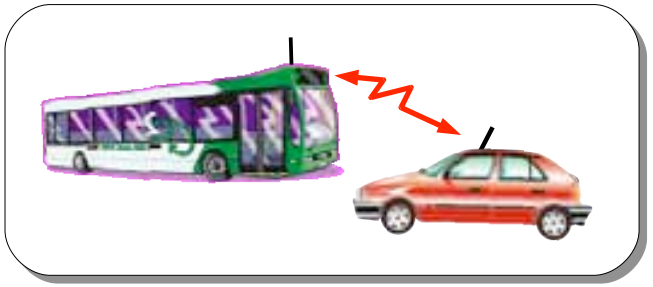
The many faces of mobile ad hoc networking

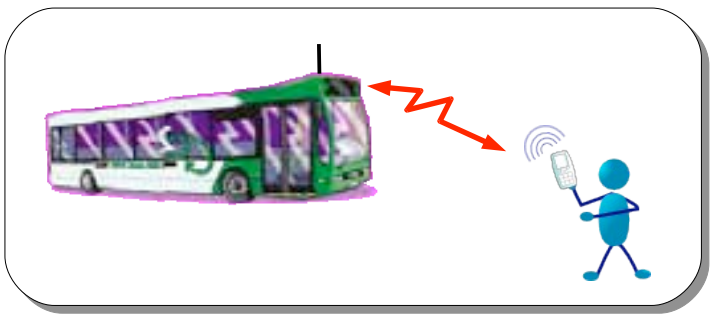












Possible application fields for mobile ad hoc networks (MANETs)

- Disaster response
  - Infrastructure systems are unavailable (non-existing and/or temporarily off-line)
  - Urgent need for communication & coordination means between members of rescue teams

Possible application fields for mobile ad hoc networks (MANETs)

- Field work “in the wild”
  - No communication infrastructure is available
  - Need for communication & coordination between scientists, engineers, etc.

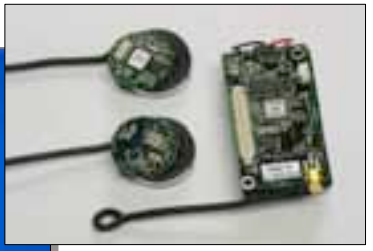
Possible application fields for mobile ad hoc networks (MANETs)

- Group / Community / “Tribal” communication
  - Communication among...
    - ... work buddies
    - ... fellow students
    - ... relatives
    - ... friends
    - etc.

Video: Campus Tohannic

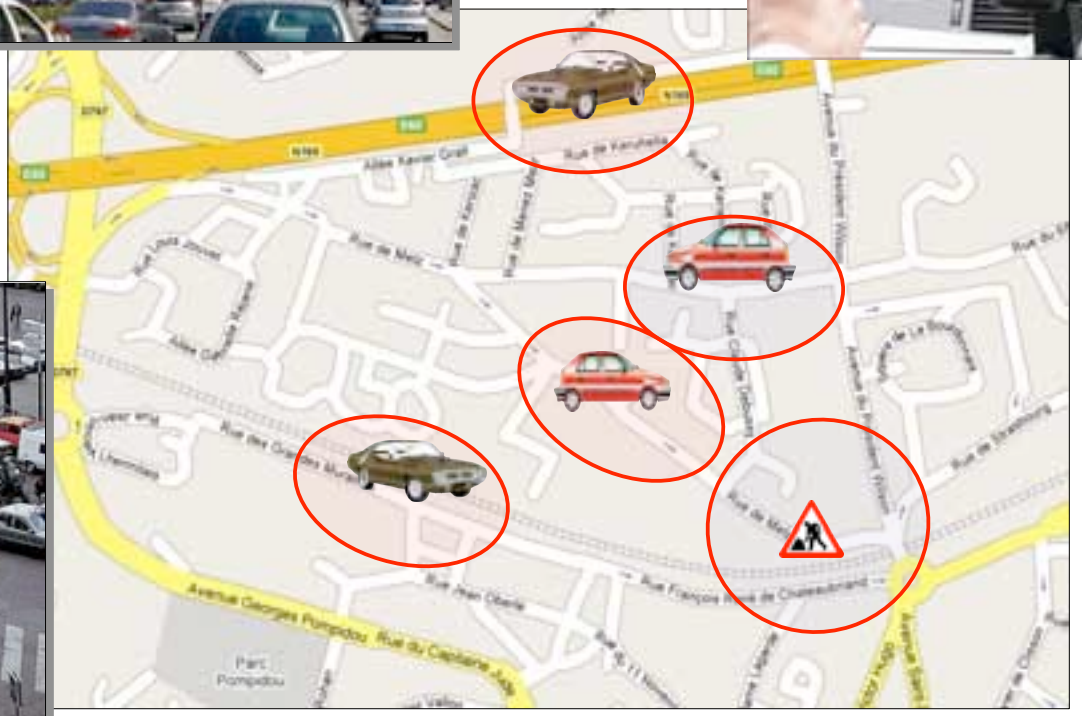
Possible application fields for mobile ad hoc networks (MANETs)

- Wildlife tracking (some form of sensor networking)



Possible application fields for mobile ad hoc networks (MANETs)

- Vehicular Ad hoc NETworking (VANET)

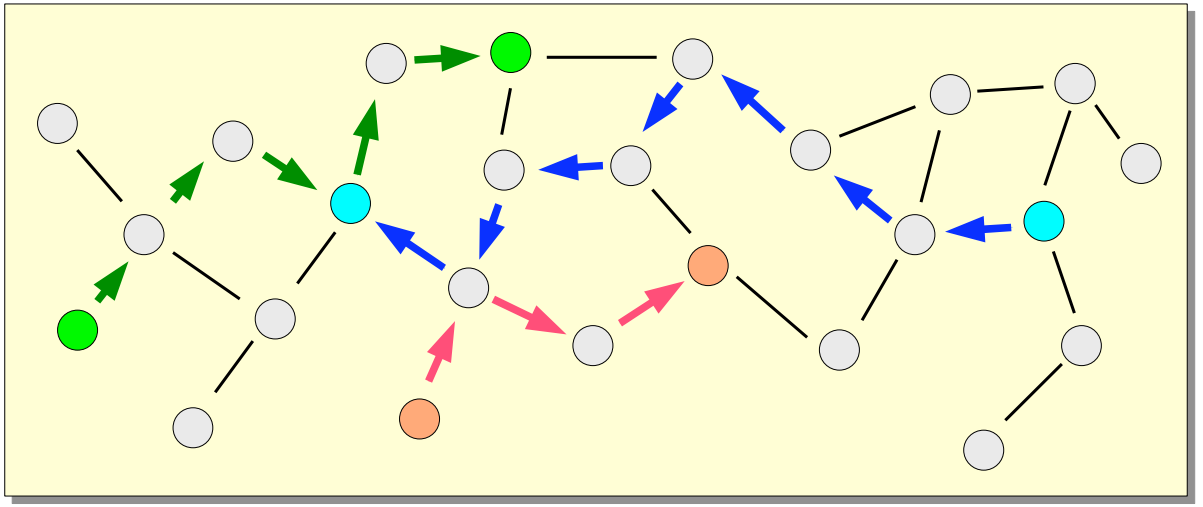


From one-hop to multi-hop communication

End-to-end communication possible thanks to dynamic routing algorithms (e.g. OLSR, AODV, DSR, DYMO, etc.)

Multi-hop communication: the obsession of the last two decades

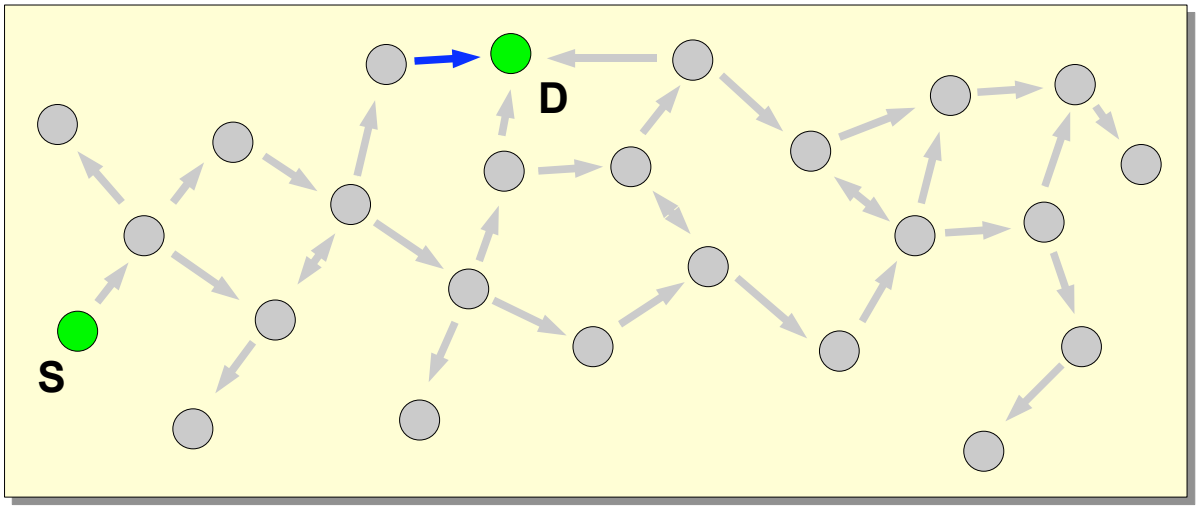
- Objective
  - "Classical" (IP) packet forwarding for unicast (multicast/broadcast) communication
- Approach
  - Every mobile host can serve as a router
  - Discovery of forwarding paths, and maintenance of these paths despite changes in the network topology
- Several (more than 60!) protocols have been designed
  - AODV, OLSR, DSR, DYMO, TORA, ZRP...
- Strong assumption
  - End-to-end connectivity
    - ↳ Sufficient **density**



Video: Dense campus

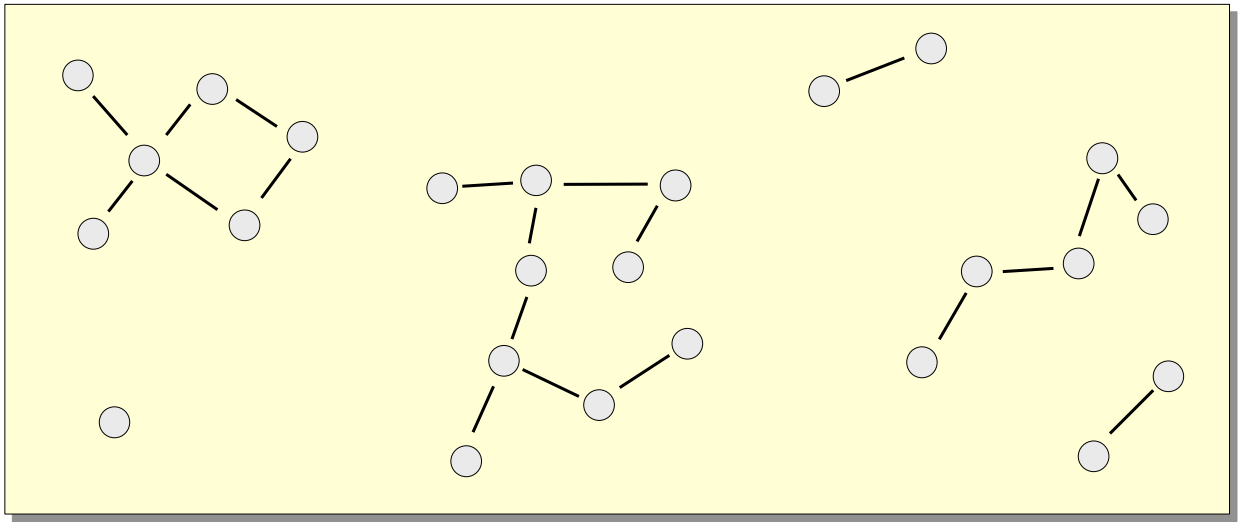
AODV: Ad hoc On-demand Distance Vector routing

- General principle
  - Reactive approach: a path from source S to destination D is sought for only when S needs to send a message to D
  - S broadcasts a Route Request (RREQ) in order to explore all possible paths to D
  - Each intermediate node...
    - rebroadcasts the request once and once only
    - records a temporary route to S
  - When D receives the request from a neighbor N it sends a Route Reply (RREP) to S via N
  - S can then send data messages to D along the same path



The problem with disconnected MANETs...

- Disconnection = absence of end-to-end connectivity
- Consequence of mobile hosts...
  - ... being sparsely distributed
  - ... being volatile (sometimes on, sometimes off)
- The network is partitioned in islands with unstable contours
- New challenge
  - Support communication despite the lack of end-to-end connectivity



No end-to-end connectivity in a MANET? Let's do without it...

- The hosts are mobile. Let us exploit this characteristic!
  - Every mobile host can...
    - *store* messages (or packets) for a while
    - *carry* messages while moving around
    - *forward* these messages to other hosts when meeting them

– *"Store, carry, and forward"* principle

- *Delay-Tolerant Networking (DTN)*
  - 🕮 *K. Fall et al. ca 2002*
    - 🕮 "Messaging in Difficult Environments" [Intel Research Report, 2004]
- *Disruption-Tolerant Networking*
- *Opportunistic Networking*

The challenges in opportunistic, delay-tolerant networking

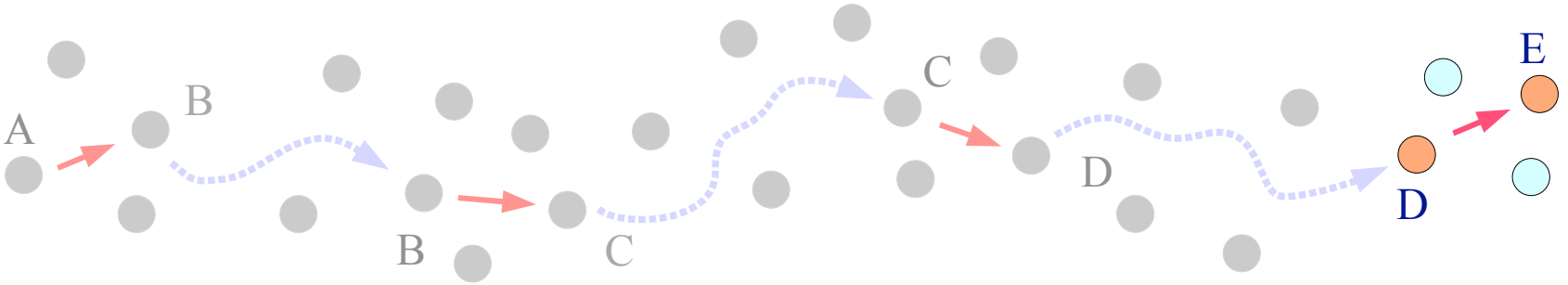
- ↗ Delivery ratio
- ↘ Delay before delivery (latency)
- ↘ Transmission cost
  - Memory consumption
  - CPU consumption
  - Power consumption
  - Radio bandwidth

A (simplistic) taxonomy of routing methods for disconnected MANETs

- At any time, each message is carried by...
  - ... a single carrier
    - Custody transfer
  - ... many (all possible) carriers
    - Epidemy / Gossiping
    - ...
  - ... several (not all) carriers
    - Controlled epidemy
    - S&W (Spray and Wait) algorithm
    - MV (Meets and Visits) algorithm
    - Oracle-based (contact prediction / utility function) algorithms
    - ...

Custody transfer

- Principle
  - A single copy of the message exists at any time
  - This copy is under the custody of a single carrier (custodian)
  - The copy is passed (ideally) only to a better carrier than the current one



- Questions: What makes a “good” carrier? What makes a “bad” one?
  - Possible selection criteria
    - Mobility pattern
    - Contact history
    - etc.
    - Trajectory
    - Available resources (power, memory)

Flooding / Epidemic forwarding

- Principle
  - All mobile hosts are enlisted to serve as carriers
  - Each carrier transfers a copy of the message to any other host it meets (unless this host is already a carrier)
- Flooding ≡ Epidemy
  - Each message is perceived as a virus or disease, that propagates in the network by "infecting" mobile hosts
  - Variations
    - Some hosts can be more or less sensible to infection
    - When a message reaches its destination, a "healing" message is used to "cure" the network

📖 A. Vahdat and D. Becker. "Epidemic Routing for Partially Connected Ad Hoc Networks" [tech. rep., Duke University, Apr. 2000]

Video: Epidemy
+ Epidemy_vs_Custody

Two extrema, and many methods in between...

- Custody transfer
  - Need to select the "good" (or best!) carriers for a message
    - ↳Need to identify at least one possible forwarding path in space and time
- Flooding / Epidemy
  - All mobile hosts are expected to serve as message carriers
    - ↳No "selection" of carriers: every host is a carrier
- Intermediate methods
  - Only a few hosts (not all of them!) are sollicited to carry a message
  - These hosts can be selected...
    - ... by design (⇒ message ferrying, infostations...)
    - ... randomly (⇒ probabilistic or semi-probabilistic methods for controlled flooding / epidemy)
    - ... based on multiple criteria (⇒ utility-based methods)

Message ferrying

- General principle
  - Exploit *non-randomness* in device movement to deliver data
  - A set of hosts called *ferries* (a.k.a. data mules) is responsible for storing and carrying messages
  - The movement of ferries is either planned in advance (e.g. bus tour) or altered according to communication needs (e.g. robots)

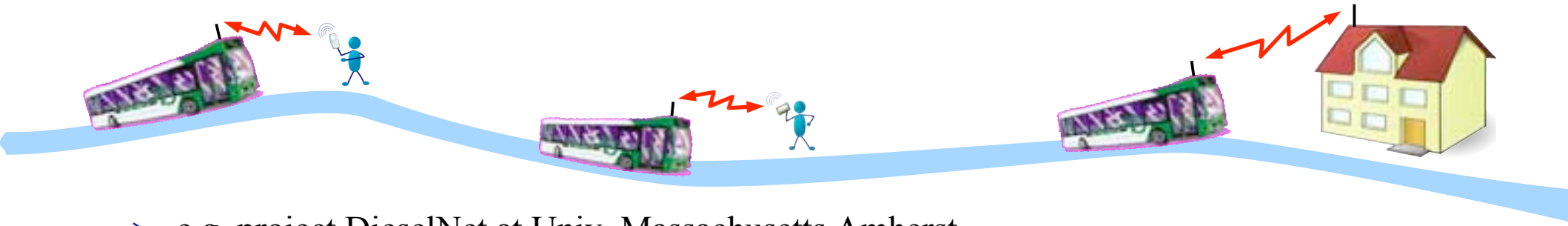
📖 W. Zhao, M. Ammar, and E. Zegura, "A Message Ferrying Approach for Data Delivery in Sparse Mobile Ad Hoc Networks" [Mobihoc'04]

📖 Q. Li and D. Rus, "Sending Messages to Mobile Users in Disconnected Ad-hoc Wireless Networks" [ICMN'00]

📖 X. Zhang, J. Kurose, B. N. Levine, D. Towsley, and H. Zhang. "Study of a Bus-Based Disruption Tolerant Network: Mobility Modeling and Impact on Routing" [Mobilcom'07]

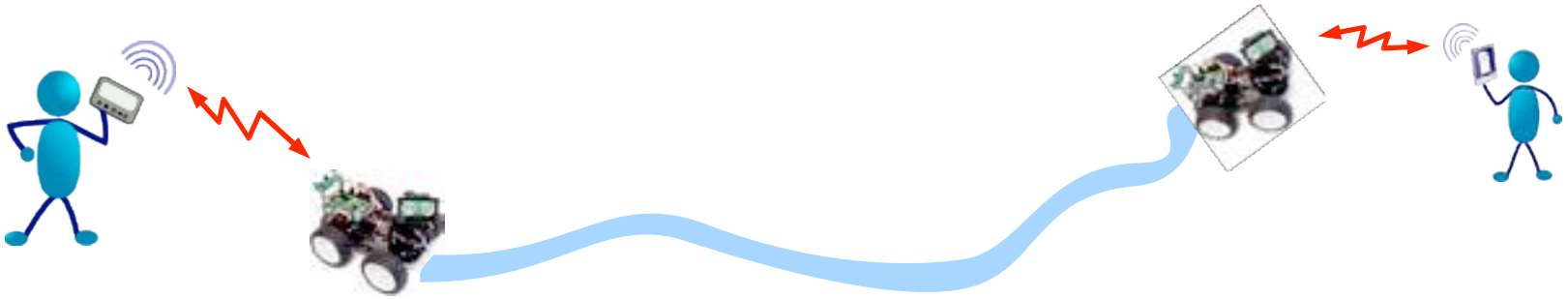
Examples of message ferrying

- Planned (regular) mobility pattern
  - Ferries are vehicles with planned tour (bus, garbage truck...)



  - e.g. project DieselNet at Univ. Massachusetts Amherst
    - 40 buses with in-board Diesel Bricks (i.e. small PC + 2 x 802.11 APs + 1 x 900 MHz radio)

- On-demand mobility
  - Ferries are robots that can move on demand towards message destinations



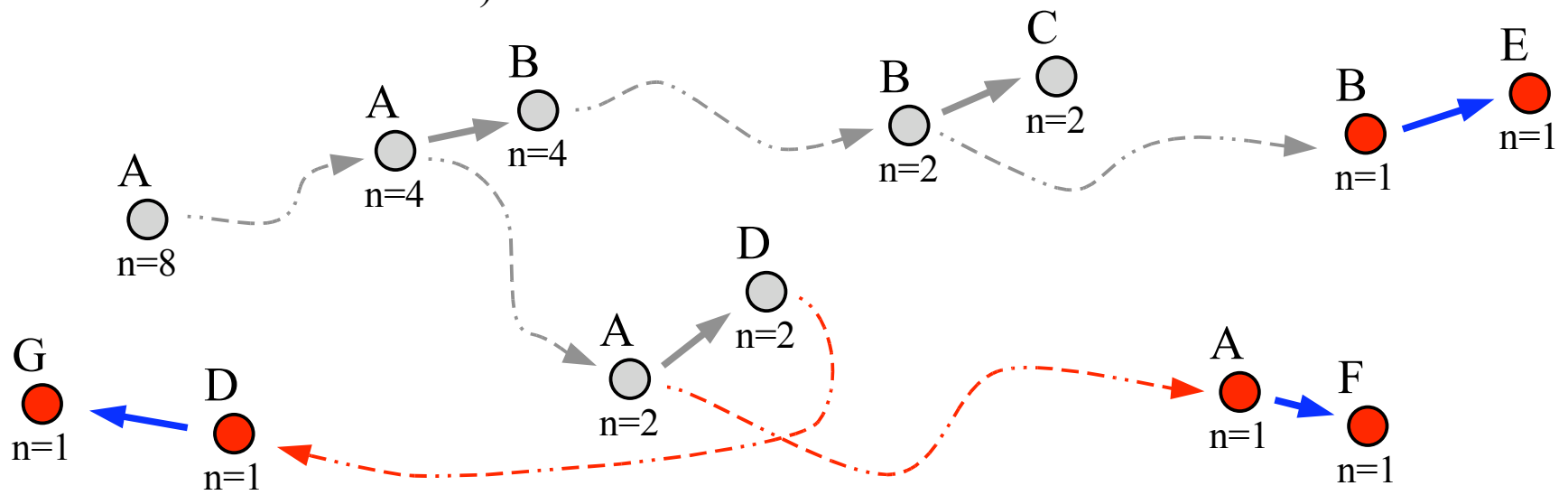
Controlled flooding / Controlled epidemy

- General principle
  - Variation on plain flooding (or on the epidemic model)
  - Only a subset of all mobile hosts are selected as carriers for each message

- Several methods
  - Reduce the scope of message propagation...
    - by setting a maximal number of hops
    - by giving each message a set lifetime (kill time)
      - 🕮 K. A. Harras, K. C. Almeroth, E. M. Belding-Royer. “Controlled Flooding in Sparse Mobile Networks” [IFIP Networking Conference'05]
    - by specifying geographical boundaries (requires geolocation capability)
  - Reduce the number of duplicates of each message...
    - using (pseudo-)probabilistic methods
    - using various algorithms (e.g. Spray & Wait)

Example of controlled flooding: Binary Spray & Wait

- General principle
  - The source of a message initially starts with L copies of this message
  - Any node P that has n > 1 message copies (source or relay), and encounters another node Q (with no copies), hands over to Q $\lfloor n/2 \rfloor$ copies and keeps $\lceil n/2 \rceil$ copies for itself
  - When a node is left with only one copy, it switches to direct transmission (i.e. waits until it meets the destination)



📖 T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and Wait: an Efficient Routing Scheme for Intermittently Connected Mobile Networks" [WDTN'05]

Video: Spray & Wait

The problem with most forms of controlled flooding / epidemy...

- What are the correct...
  - ... number of hops
  - ... message lifetime
  - ... number of duplicates (e.g. Spray & Wait)
  - ... duplication ratio (probabilistic method)
  - etc.

  ... to reach a particular destination at minimal (or reasonable) cost?!?

- Hard to tell, unless the characteristics of the network are known precisely
  - e.g. geographical boundaries
  - e.g. mobility pattern (speed, directions, trajectories, schedules...)
  - e.g. number of mobile hosts

  ✋ In a particular environment, parameters can be tuned by trial and error

Video: Epidemy with short lifetime

“Socially-aware” networking

- Target MANETs composed of digital devices that are carried by human beings
- Basic assumption
  - Human beings do not move randomly(!!!)
  - They tend to exhibit regular mobility patterns and/or contact patterns
    - Each individual visits periodically the same places (workplace, shops, sports club, home...)
    - Each individual meets regularly the same persons (colleagues, friends, relatives...)
- Objective
  - Capture and exploit these characteristics of human mobility and social interaction

Contact prediction in "socially-aware" networks

- General principle
  - Each node maintains a history of its contacts with other nodes
  - This history is used to identify periodic contact patterns and thus estimate the probability of future contacts
  - Whenever host A (which has a message for host C) meets host B, B estimates its chance of meeting C in the future. If B looks like a good carrier (or better carrier than A) to reach C, then A forwards the message to B
- Possible (and desirable) improvement
  - Transitivity: whenever two nodes meet, they exchange summaries of their prediction vectors

📖 A. Lindgren, A. Doria, and O. Schelen. "Probabilistic Routing in Intermittently Connected Networks (PROPHET)" [SAPIR'04]

📖 M. Musolesi, S. Hailes, and C. Mascolo. "Adaptive Routing for Intermittently Connected Mobile Ad Hoc Networks" [WoWMoM'05]

📖 C. Boldrini, M. Conti, J. Jacopini, and A. Passarella. "Hi-BOp: a History Based Routing Protocol for Opportunistic Networks" [WoWMoM'07]

Example of a protocol using a contact prediction oracle

- PROPHET: **P**robabilistic **RO**uting **P**rotocol using **H**istory of **E**ncounters and **T**ransitivity
- General principle
  - Define a probabilistic metric, $P \in [0, 1]$, that in some sense reflects the probability that a node will be encountered in the future
  - Use this metric when deciding who to forward a message to
  - Update the probabilistic metric of a node upon encounter

$$P_{(a,b)} = P_{(a,b)_{old}} + (1 - P_{(a,b)_{old}}) \times P_{init}$$

  - The probabilistic metric has a transitive property

$$P_{(a,c)} = P_{(a,c)_{old}} + (1 - P_{(a,c)_{old}}) \times P_{(a,b)} \times P_{(b,c)} \times \beta$$

  - Decrease the value as the metric ages

$$P_{(a,b)} = P_{(a,b)_{old}} \times \gamma^{k}$$

  - Simple forwarding strategy used
    - Forward message to all encountered nodes with higher P-value than yourself for the given destination

The problem with “socially-aware” methods...

- Are they scalable?
  - Each mobile host must collect, store, and process information about its past contacts with other hosts
  - Is it applicable in large MANETs (i.e. with thousands or millions of hosts)?...
- What about mobile hosts (and users)...
  - ... that are not really sociable?
  - ... that do not belong to a closely-knit community?

Beyond unicast/multicast/broadcast forwarding: Content-Based Networking (CBN)

- General principle
  - The flow of information is interest-driven rather than destination-driven
  - Receivers specify (subscribe for) the kind of information they are interested in, without regard to any specific source
  - Senders simply send (publish) information in the network without addressing it to any specific destination

☞ Typical API: publish/subscribe

📖 A. Carzaniga and A. L. Wolf, "Content-based Networking: a New Communication Infrastructure" [WIMWS'01]

An implementation of CBN in disconnected MANETs

- General principle
  - Document-oriented, content-driven epidemy
  - Each host is selective regarding the documents it...
    - ... wishes to receive (subscription ≡ definition of local interest profile)
    - ... accepts to store, carry, and forward
  - When two hosts meet, they only exchange documents that match each host's interest profile

- Several variants
  - Exchanges between 1-hop neighbours only
  - Exchanges between N-hop neighbours
    - ☝Requires support for multi-hop broadcast and unicast communication in connected fragments (islands) of the MANET

📖 J. Haillot, F. Guidec. "A Protocol for Content-Based Communication in Disconnected Mobile Ad Hoc Networks" [AINA'08]

Video : One_Hop_Sel_vs_Non_Sel.avi

Documents and interest profiles

- Document = descriptor + payload
- Descriptor = set of tuples (attribute="value")

```
<descriptor
    id="254d3g645d6s45f6"
    date="Sun Jun  1 10:08:16 CEST 2008"
    deadline="Sun Jun  1 14:08:16 CEST 2008"
    from="Fred"
    newsgroup="comp.networking"
    keywords="mobile,ad hoc,delay-tolerant, \
                opportunistic,gossip-based"
/>
```

Payload

```
<pattern
    from="Fred|Julien|Nicolas"
    newsgroup="comp.*"
/>
```

```
<pattern
    newsgroup="comp.networking"
    keywords="mobile|opportunistic"
/>
```

```
<pattern
    date="Sun Jun  1 .*"
    priority="high"
/>
```

- Interest profile = list of patterns that allow a host to differentiate documents based on their descriptors

And what about software applications?...

- Observation

> Opportunistic / Delay-tolerant networking
> is **not** equivalent to
> traditional Internet-based networking

- Wise guidelines for application design
  - There's no guaranty about eventual message delivery
    - Admit this is unreliable communication, and develop resilient applications (and high-level protocols or middleware) accordingly
  - There's no guaranty about when messages are delivered
    - Think "asynchronous"!
  - There's no temporaneous end-to-end connectivity
    - Forget about TCP, and about TCP-based protocols (e.g. SMTP, NNTP, HTTP...)
    - Forget about the client-server model. Think "peer-to-peer"!

Typical proof-of-concept applications for human-to-human interaction

- Electronic mail
  - 🕮 T. Hyyryläinen, T. Kärkkäinen, C. Luo, V. Jaspertas, J. Karvo, and J. Ott. “Opportunistic Email Distribution and Access in Challenged Heterogeneous Environments” [CHANTS’07]
- Discussion systems (“à la Usenet”)
  - 🕮 J. Haillot and F. Guidec. “Towards a Usenet-like Discussion System for Users of Disconnected MANETs” [WON'08]
- Filesharing / Information dissemination
  - 🕮 J. Leguay, A. Lindgren, J. Scott, T. Friedman, J. Crowcroft. “Opportunistic Content Distribution in an Urban Setting” [CHANTS '06]
  - 🕮 V. Lenders, G. Karlsson, and M. May. “Wireless Ad Hoc Podcasting” [SECON’07]
- Deployment of software components / Software updates
  - 🕮 H. Roussain and F. Guidec. “Cooperative Component-Based Software Deployment in Wireless Ad Hoc Networks” [CD'05]
- Discovery and invocation of distributed services
  - 🕮 Y. Mahéo, R. Said and F. Guidec. “Middleware Support for Delay-Tolerant Service Provision in Disconnected Mobile Ad Hoc Networks” [IPDPS'08]

Conclusion

- Opportunistic delay-tolerant communication in disconnected MANETs
  - Not a threat to infrastructure-based communication!
  - Sometimes a complement, sometimes an alternative
- No single, general-purpose protocol or method
  - def. "ad hoc": a solution designed for a specific problem or task, non-generalizable, and which cannot be adapted to other purposes
- Hot topics
  - Experimentation in real conditions (with plenty of users, plenty of applications...)
  - Scalability?!?
  - Security (no PKIs!)
  - Incentives (same problems as in "standard" MANETs + delay-tolerance + network fragmentation)

http://www-valoria.univ-ubs.fr/CASA