Multihop Wireless Ad Hoc Networking: Current Challenges and Future Opportunities

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Monarch Project

Traditional Wireless Networks

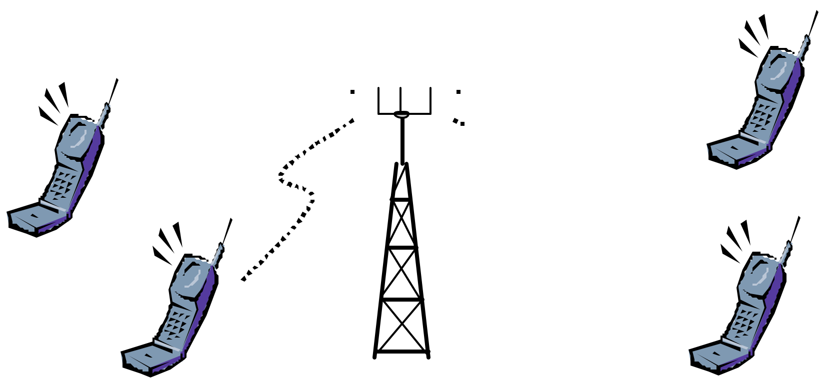
Many forms, but all have similar architecture:

- Wireless cellular networks, wireless LANs, …

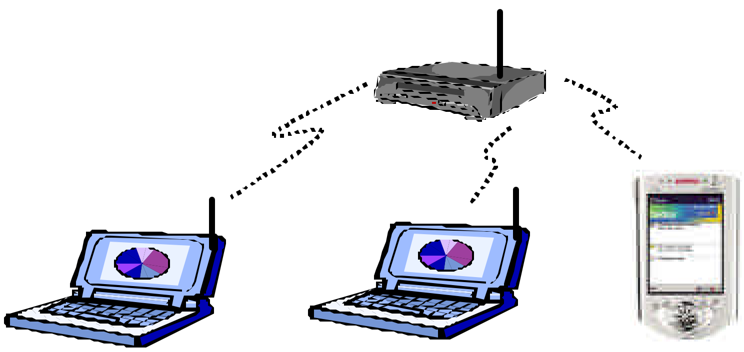
Relies on a fixed infrastructure:

- Centralized base station or access point
- All users within wireless range of it
- Needs planning, installation, management, …

Wireless Cellular



Wireless LAN



Wireless Ad Hoc Networking

May be no network infrastructure available:

- Remote areas
- Unplanned meetings
- Emergency relief personnel quickly deployed
- Military troops

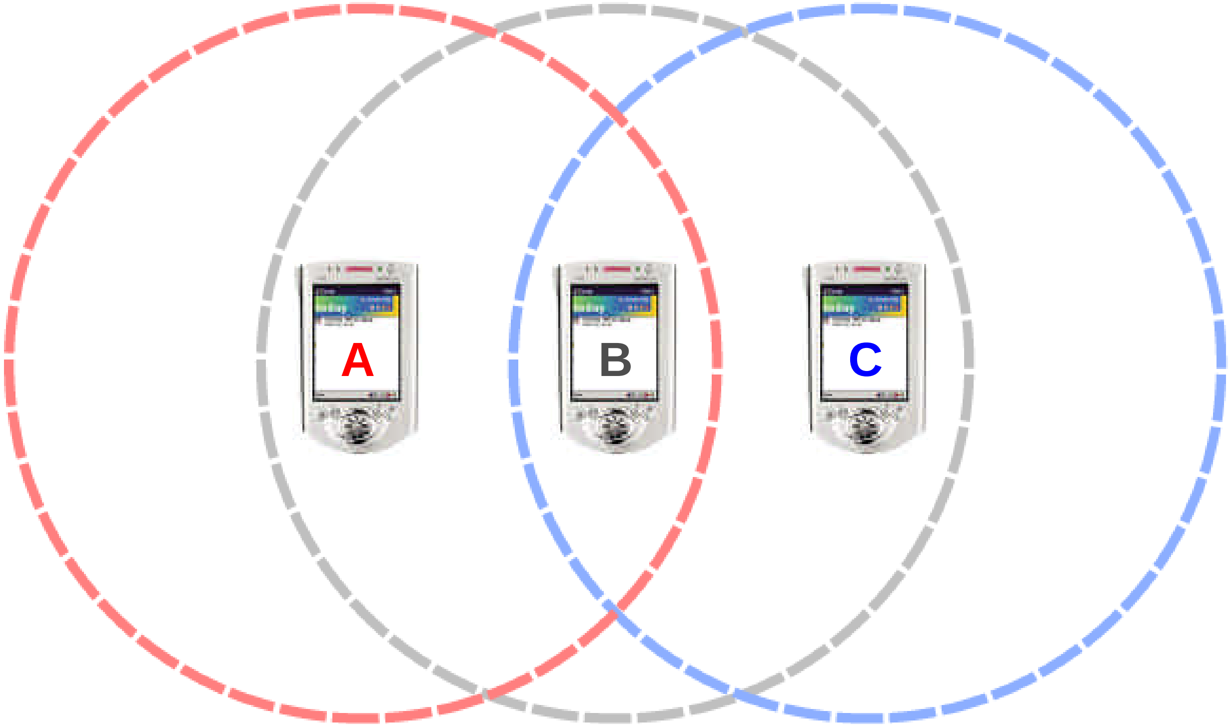
May not want to use the available infrastructure:

- Time or cost to access and register on the service
- Performance or capacity of existing service and infrastructure

Dynamically extend coverage of infrastructure:

- Allow users to be further away from infrastructure

Ad Hoc Network Routing

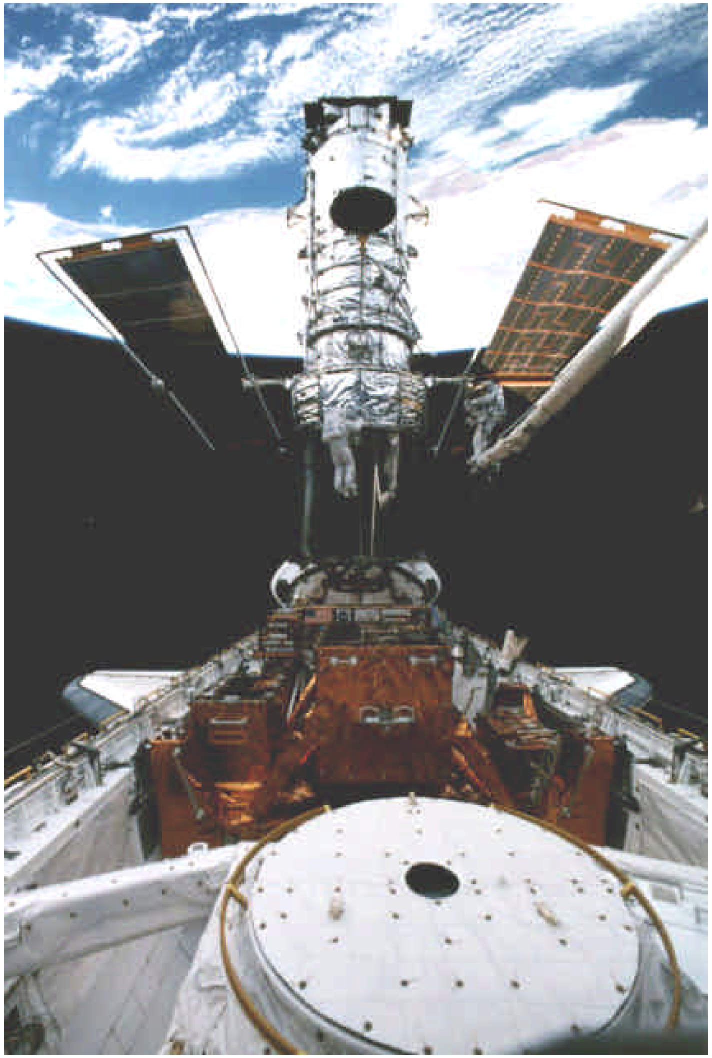


- May be out of wireless transmitter range of others
- Need to use other nodes as routers for forwarding
- Find new routes after movement or change

New Example Use: Caterpillar

- Vehicle, production monitoring
- Advanced robotic/autonomous applications

New Example Use: NASA



Major Ad Hoc Networking Programs

DARPA/ARPA programs:

- Packet Radio Network (PRNET), 1972–1983
- Survivable Adaptive Networks (SURAN), 1983–1992
- Global Mobile Information Systems (GloMo), 1995–2000

Internet (IETF):

- Mobile Ad Hoc Networks (MANET) Working Group, since 1997
- IRTF Ad Hoc Networks Scalability (ANS) Research Group, since 2003

Many others:

- University, military, and industry research projects
- Commercial systems from FireTide, MeshNetworks, PacketHop Networks, SkyPilot Network, Tropos Networks, **...**

General Ad Hoc Network Challenges

More constrained than in traditional networks:

- Limited device resources (e.g., CPU, battery)
- Limited network resources (shared bandwidth)

Dynamic network environment:

- Nodes may move at any time (and often)
- Nodes may join and leave the network
- Wireless propagation is highly variable

Self-organized and operated network:

- No one is "in charge"
- No one to provide standard services

Types of Ad Hoc Network Routing Protocol

Periodic (proactive) routing protocols:

- Most wired routing protocols are periodic
- Examples: distance vector and link state routing
- Routing learned and spreads periodically
- Trades off simplicity, delay, and routing overhead
- Examples: DSDV, TBRPF, OLSR, …

On-demand (reactive) routing protocols:

- Discover routing information only when needed
- Routing overhead scales automatically
- Better in resource-limited, dynamic networks
- Examples: DSR, AODV, …

Hybrid combinations of proactive and reactive mechanisms

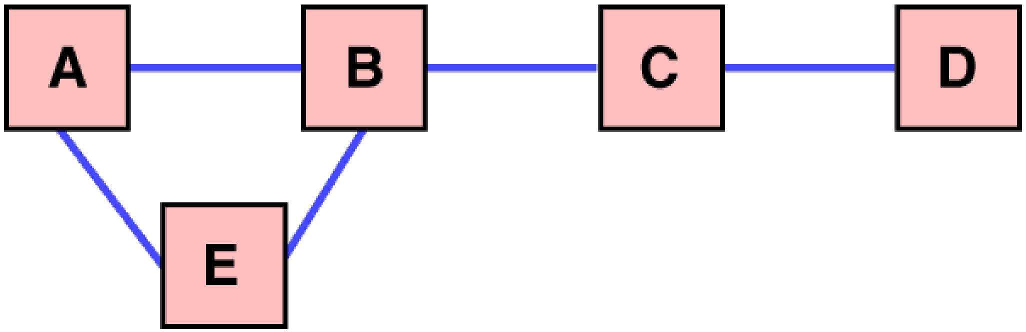
Example Proactive (Periodic) Routing

Basic distance vector routing:

- Nodes keep a ***routing table***, try to maintain up-to-date routes for all possible destinations
- All nodes periodically broadcast routing update
- Tells your neighbors the length of your best route to each destination
- They know they can reach each with distance 1 hop more by routing through you
- This is the distributed ***Bellman-Ford algorithm***
- DSDV protocol adds a ***sequence number*** for each update, guarantees no routing loops

Distance Vector Operation

Example routing table at node A:



Node A's table

Dest	Next Hop	Dist
A	—	0
B	B	1
C	B	2
D	B	3
E	E	1

- Each node periodically broadcasts its routing table (one hop, to its neighbors)
- Nodes remember the best route to each destination
- After missing several updates from a neighbor, node sets distance to "infinity"

Example Reactive (On-Demand) Routing

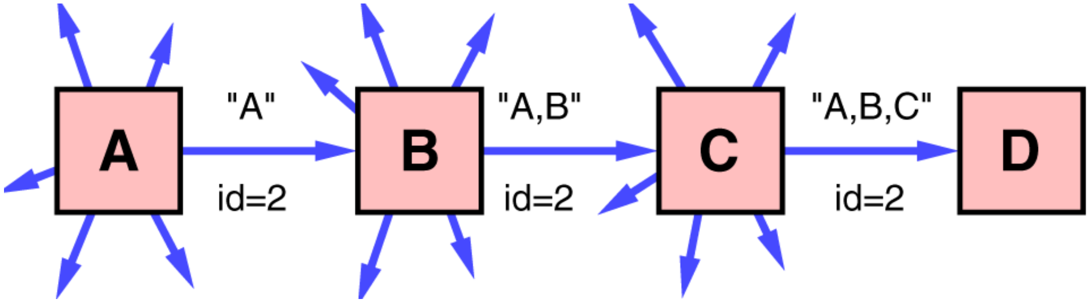
The Dynamic Source Routing protocol (DSR):

- Divides routing problem into two parts:
  - ***Route Discovery***: only try to find route when you don't have one and need one
  - ***Route Maintenance***: only while you're actually using a route, try to keep working or fix it
- All parts of protocol operate entirely ***on-demand***
- Ignores all topology changes not affecting you
- Overhead scales automatically with movement
- No overhead when stationary and found routes

Basic DSR Route Discovery

To discover a route to some address:

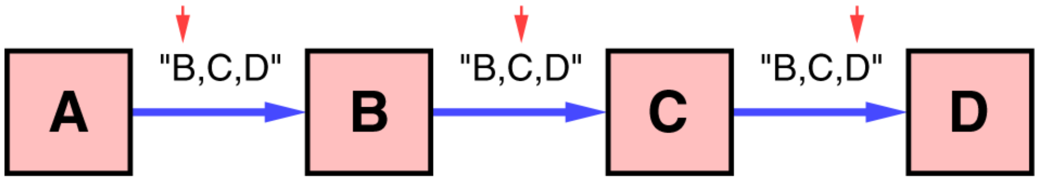
- Broadcast ROUTE REQUEST with unique request id
- When receiving a ROUTE REQUEST:
  - If target is yourself, return the recorded route to the initiator in a ROUTE REPLY
  - Else, if recently seen this id, drop the REQUEST
  - Otherwise, append your own address and rebroadcast the ROUTE REQUEST



Basic DSR Route Maintenance

After transmitting a packet to the next hop:

- Listen for link-level per-hop acknowledgement, or
- Listen for that node sending packet to next hop, or
- Set a bit in the packet to request explicit next-hop acknowledgement



When a problem with forwarding is detected:

- Send a ROUTE ERROR to original sender
- Sender removes the broken link from its Route Cache

Some General Routing Challenges (1/2)

Routing information is expensive to acquire:

- Ongoing overhead (periodic) or burst when needed (on-demand) to search for route
- Consumes network resources, which are limited and must be shared by all nodes in area
- Consumes node resources (battery, CPU, etc.), which are limited, and battery is finite
- You can never collect (and keep collecting) all routing information

Some General Routing Challenges (2/2)

Routing information will always be incomplete:

- Hard to distribute information to "all nodes" without fixed membership, with mobility, with partitions, etc.
- Information may be "summarized" the further you get from its source

Routing information will always be out-of-date:

- Impossible to exchange information "continuously" or "immediately"
- The nodes can move at any time
- Wireless radio propagation is highly variable

Ad Hoc Network Scalability

Physical limits:

- ***Gupta and Kumar:*** In a static network, throughput for each source-destination pair $O(1/\sqrt{N})$, for N nodes
[IEEE Transactions on Information Theory, March 2000]
- ***Grossglauser and Tse:*** In a mobile network, throughput can remain constant, but with increased latency
[IEEE/ACM Transactions on Networking, August 2002]

Routing protocol scalability:

- ***Proactive routing:*** size of update packets proportional to number of nodes in the network
- ***Reactive routing:*** Overhead of route discovery search can be proportional to number of nodes in the network

Improving Physical Scalability

Power control:

- Transmit at minimum power needed to reach next hop
- Saves energy too, but difficult to preserve collision avoidance

Directional antennas:

- Point transmit antenna in direction of omnidirectional receiver
- Even better to also point receiver at transmitter, but difficult to know when/where to point
- And also hard to preserve collision avoidance

Multiple radios/channels:

- Choose best channel, exploit frequency diversity
- Pipeline forwarding packets across multiple channels
- Multiple radios at a node can transmit and receive at once

Improving Routing Scalability

Routing hierarchy or locality:

- Localize route discovery flood using geographical location
- Localize assuming new route has many nodes in common with old route that just broke
- Examples: Location Aided Routing, Query Localization
- Route within lower hierarchical level, between higher “clusters”
- Example: Zone Routing Protocol (ZRP)

Geographical routing:

- No traditional routing state, saves memory/network overhead
- Greedy forwarding to neighbor closest to destination
- Route around perimeter of void to get “out of a corner”
- Example: Greedy Perimeter Stateless Routing (GPSR)

Ad Hoc Network Security

Ad hoc networks depend on honest cooperation:

- You forward packets correctly and honestly for me, and
- I'll forward packets correctly and honestly for you

Two general areas of security to address:

- Lack of cooperation
- Forging routes and maliciously breaking routes

Some types of ad hoc network can be "easily" secured:

- Single network-wide shared secret key
- Encrypt and authenticate all packets with this one key
- Only valid members of the network can participate
- But not useful for general situations and doesn't handle compromised nodes

Not Provided by Standard Security Services

Standard security services can be classified as:

- ***Integrity:*** Message has not been tampered with
- ***Authentication:*** Message comes from claimed node, and also has not been tampered with
- ***Non-Repudiation:*** Can prove that the message comes from claimed node, and also has not been tampered with

None of these satisfy ad hoc network security needs:

- Can't force nodes to cooperate or detect all cases when they do not
- Can't protect against a compromised node sending malicious routing packets

Cooperation in Ad Hoc Networks

Nodes may agree to be part of a route but not forward data:

- On demand routing: Forward ROUTE REQUEST packets as normal (and ROUTE REPLY packets)
- Distance vector routing: Maintain routing table and send periodic routing advertisement packets as normal

Biggest reasons for lack of cooperation:

- ***Selfish:*** Unwilling to spend battery life, CPU cycles, or network bandwidth around itself, even though expects other nodes to forward its data
- ***Malicious:*** Dropping data packets is a Denial-of-Service attack

Some solutions: Observation/reputation, Economics/game theory

Some Routing Security Threats

Attacker forges or modifies a routing packet:

- DSDV: change next hop, distance, or sequence number
- DSR: remove, add, or reorder hops, or send fake Route Errors
- Can cause misrouting or Denial-of-Service

Exploiting the protocol to consume resources:

- Excessive Route Discovery floods in DSR
- Fake routing packets that must be checked and discarded (if you can detect they are fake)

Not forwarding data packets along a route

Our solutions mainly make use of ***secure one-way hash chains*** (Ariadne is secured DSR, SEAD is secured DSDV)

TCP over Ad Hoc Networks

TCP in general wireless and mobile networks:

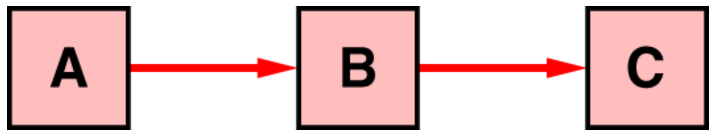
- TCP is heavily tuned to work well in modern ***wired*** networks
- Any dropped or delayed ACK is assumed to mean ***congestion***

Many additional challenges in ad hoc networks:

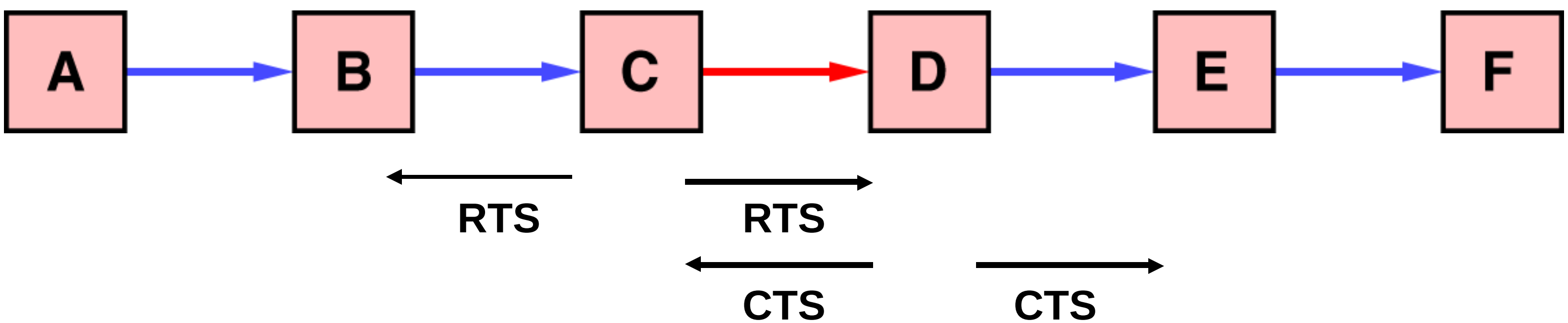
- More than one wireless intermediate forwarding node (not just the base station)
- Generally more frequent mobility events
- Frequently changing set of intermediate nodes
- Frequently changing number of intermediate nodes
- No nice wired backbone to coordinate over
- Intermediate nodes receive and forward on same radio channel
- Other nodes around you cause increased, variable interference

Fundamental Limits

Nodes receive and forward on same radio:

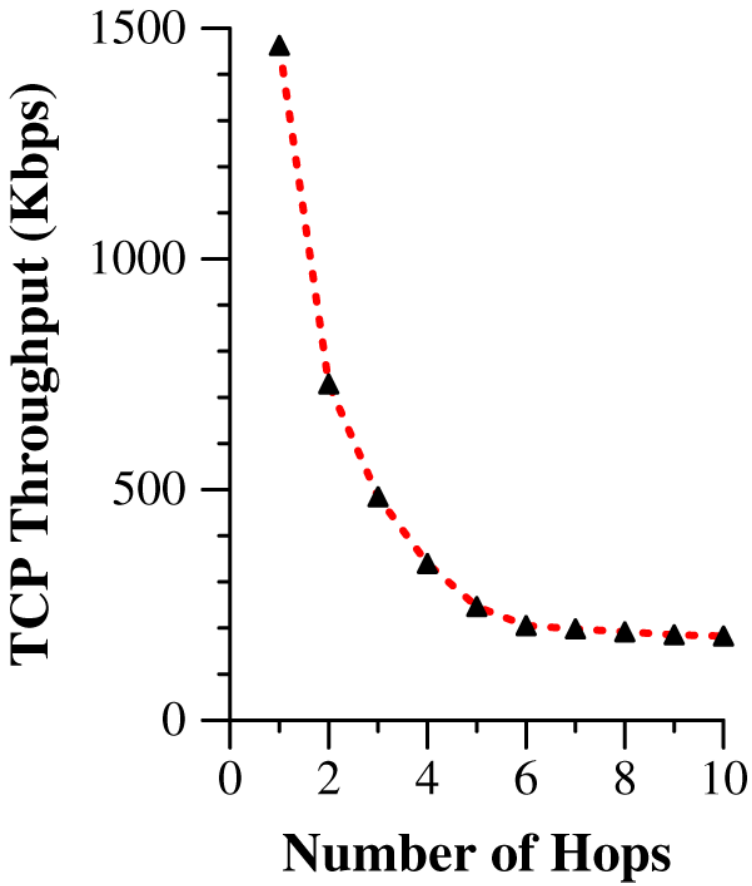


Beyond that, MAC protocol must still make intermediate nodes defer (RTS, CTS, physical carrier sense):



Simulated Multihop TCP Performance

TCP performance in a ***stationary*** multi-hop network:



# Hops	Throughput (kbps)
1	1463.0
2	729.0
3	484.4
4	339.9
5	246.4
6	205.2
7	198.1
8	191.8
9	185.3
10	182.4

Expected Multihop Throughput

Weighted average for a TCP connection:

- T_i is throughput for an *i*-hop TCP connection
- t_i is amount of time TCP connection uses *i* hops

$$\textbf{\textit{expected throughput}} = \frac{\sum_{i=1}^{\infty} t_i \times T_i}{\sum_{i=1}^{\infty} t_i}$$

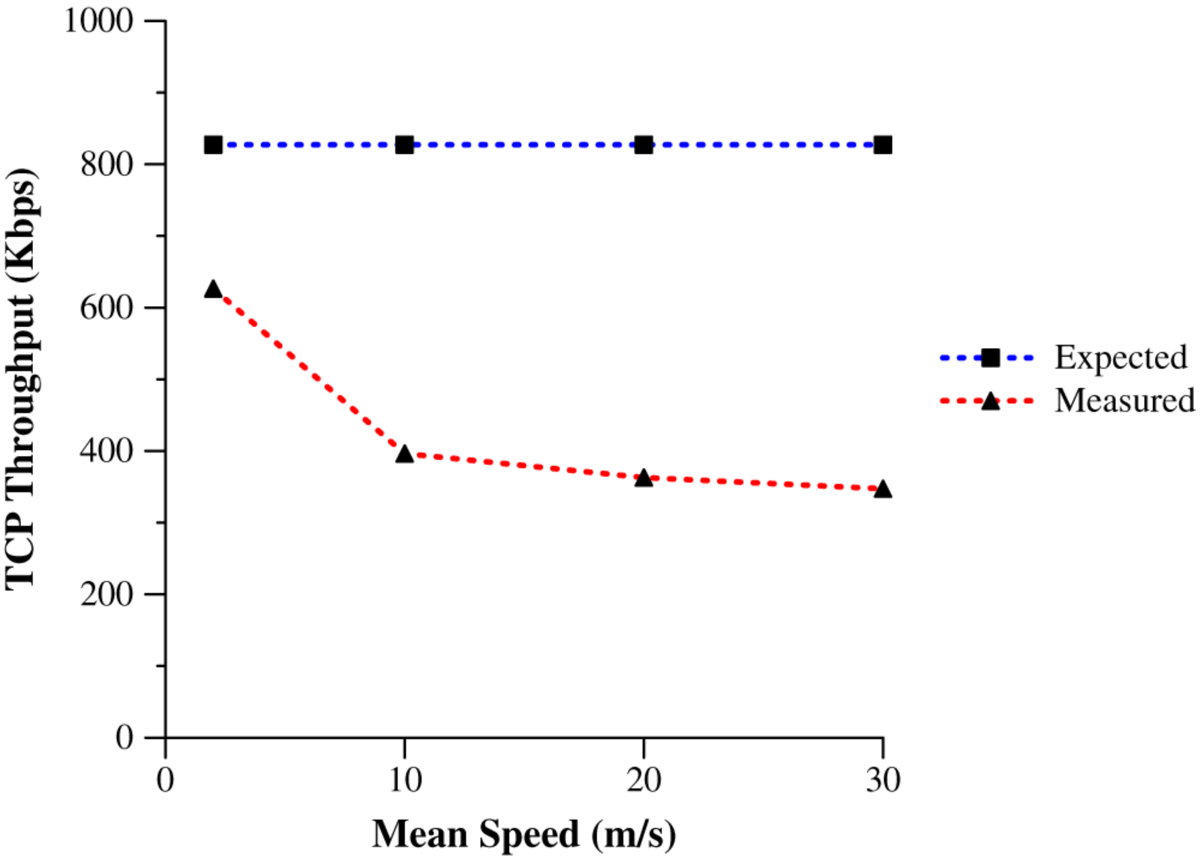
Expected throughput is only defined for a specific connection

Depends on particular movement pattern and timing

Expected vs. Measured Throughput

Expected throughput is approximate upper bound:

- May not always use shortest possible routes
- Routing protocol causes its own overhead



Peer-to-Peer vs. Ad Hoc Networking

In many ways these are very similar:

- Peer computers cooperating in a network
- Self-forming and maintaining

But they are very different in all the details:

- Peer-to-peer networking:
  - Assumes low-level routing exists (e.g., Internet)
  - Main task is to find ***which node*** has some object (e.g., file)
- Ad hoc networking:
  - No routing exists yet at all
  - Main task is to find a route (sequence of hops) leading to some ***known destination node***

Integrating P2P and Ad Hoc

Safari project at Rice University:

- Self-organizing, adaptive network hierarchy
- Scalable ad hoc network routing (10s of thousands of nodes)
- Self-organizing higher layer network services and applications
- Integrated with Internet infrastructure where it exists

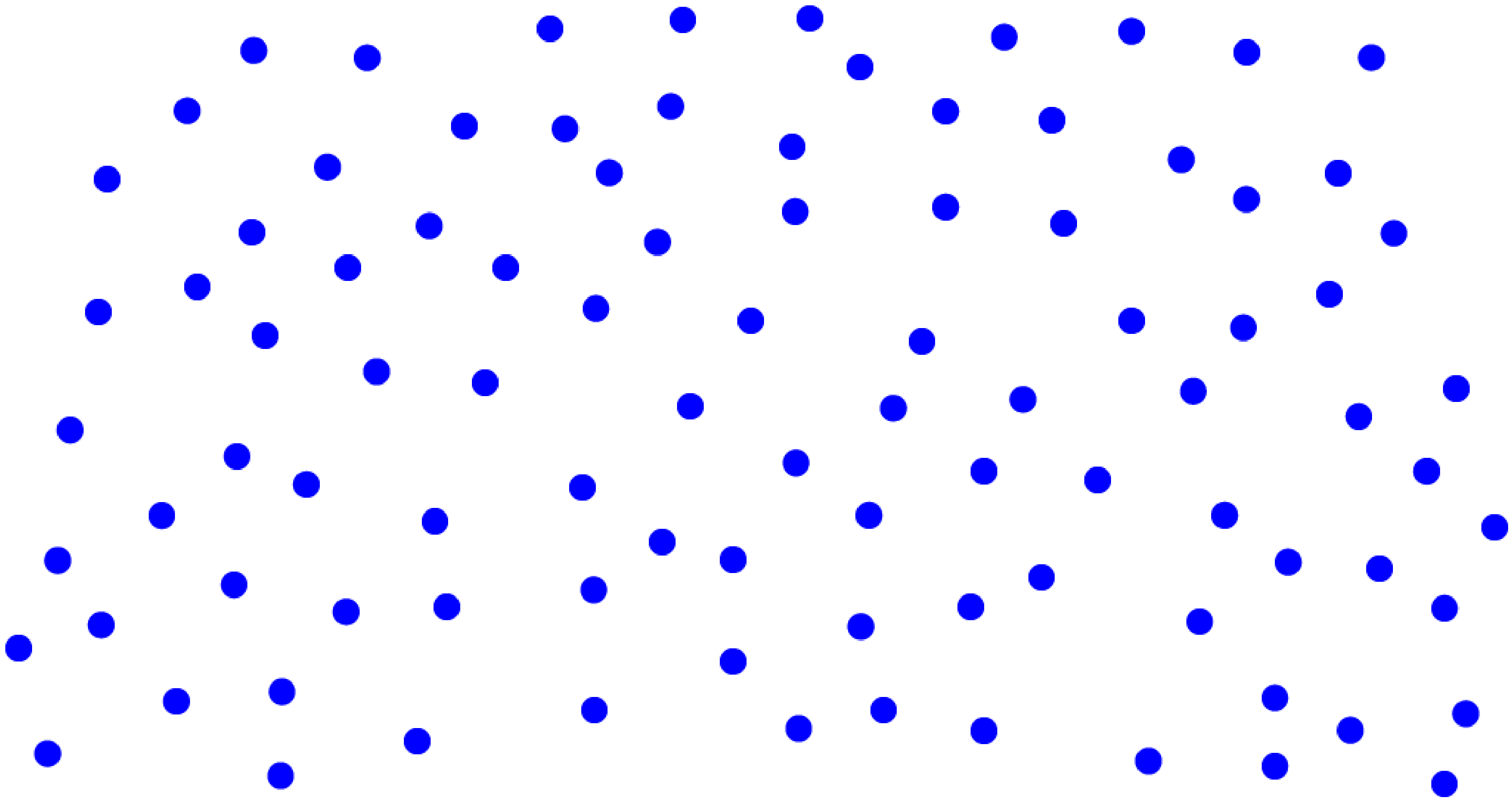
Safari leverages and tightly integrates two areas of research:

- Ad hoc networking
- Peer-to-peer networking

Builds an adaptive, ***proximity-based hierarchy*** of cells and leverages this for scalable ***routing*** and higher layer ***services***

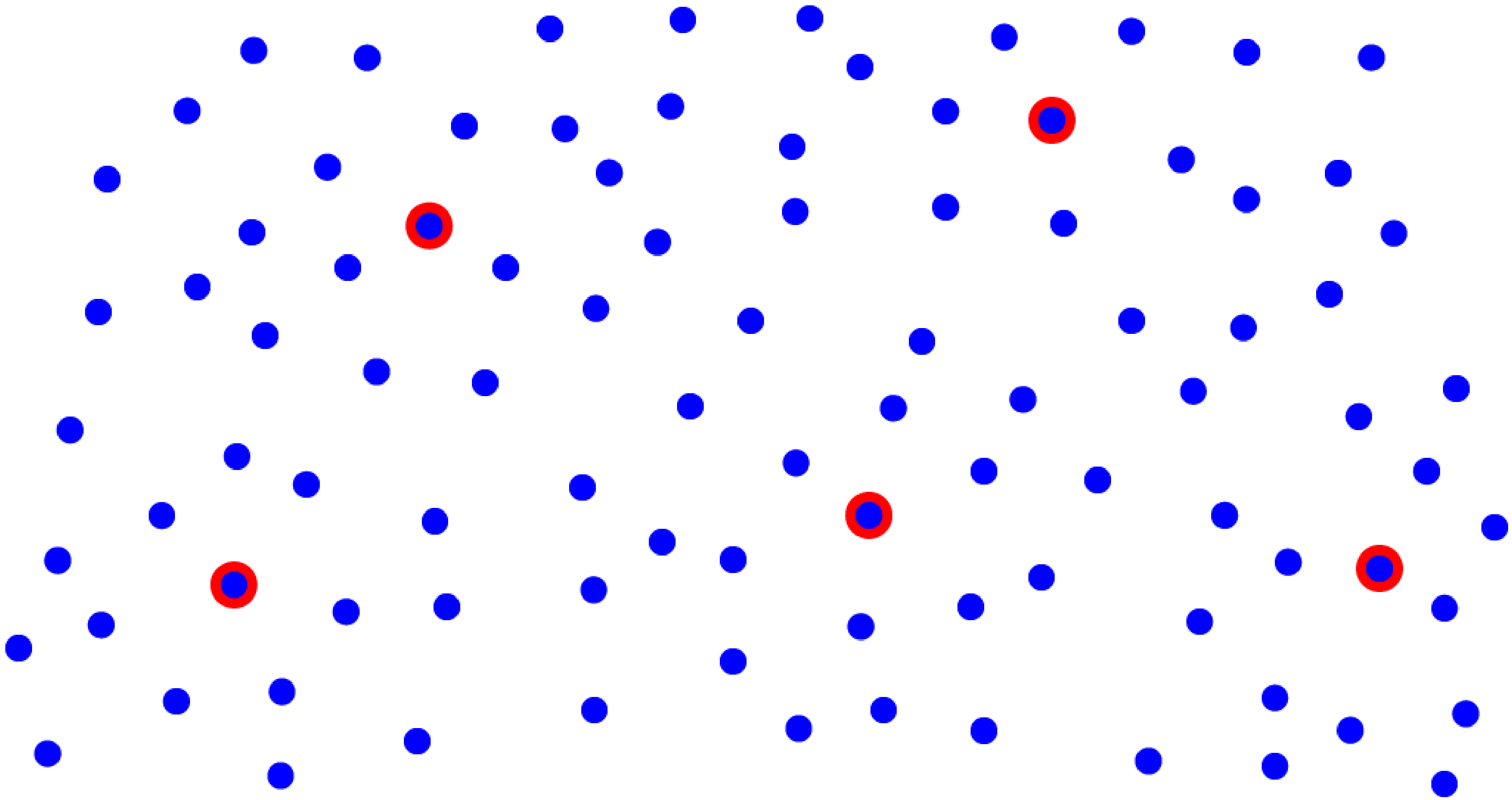
Safari Hierarchy Self-Organization

All nodes are equivalent – no specialized nodes assumed:



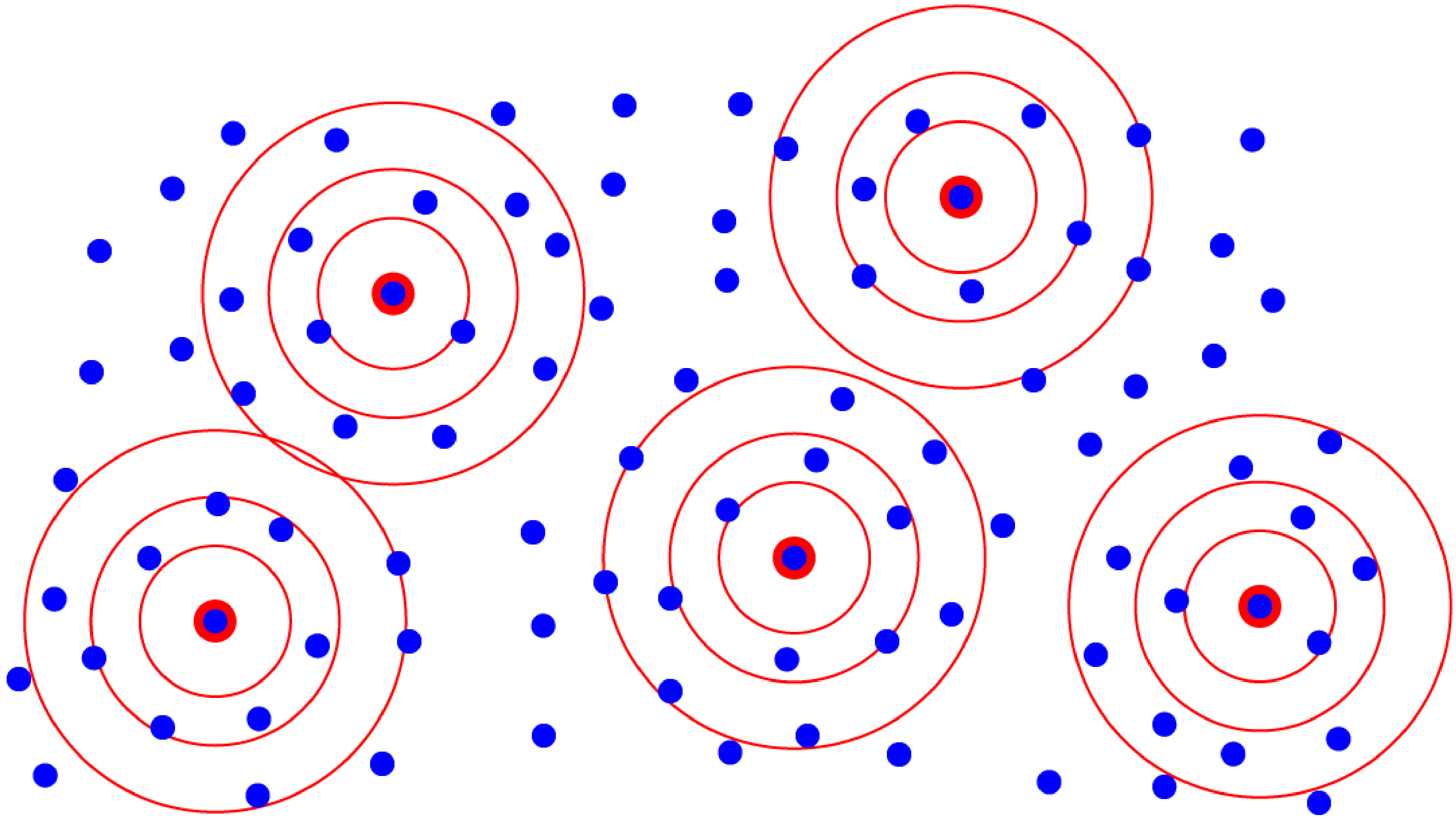
Safari Hierarchy Self-Organization

Nodes self-elect to become a ***drum***:



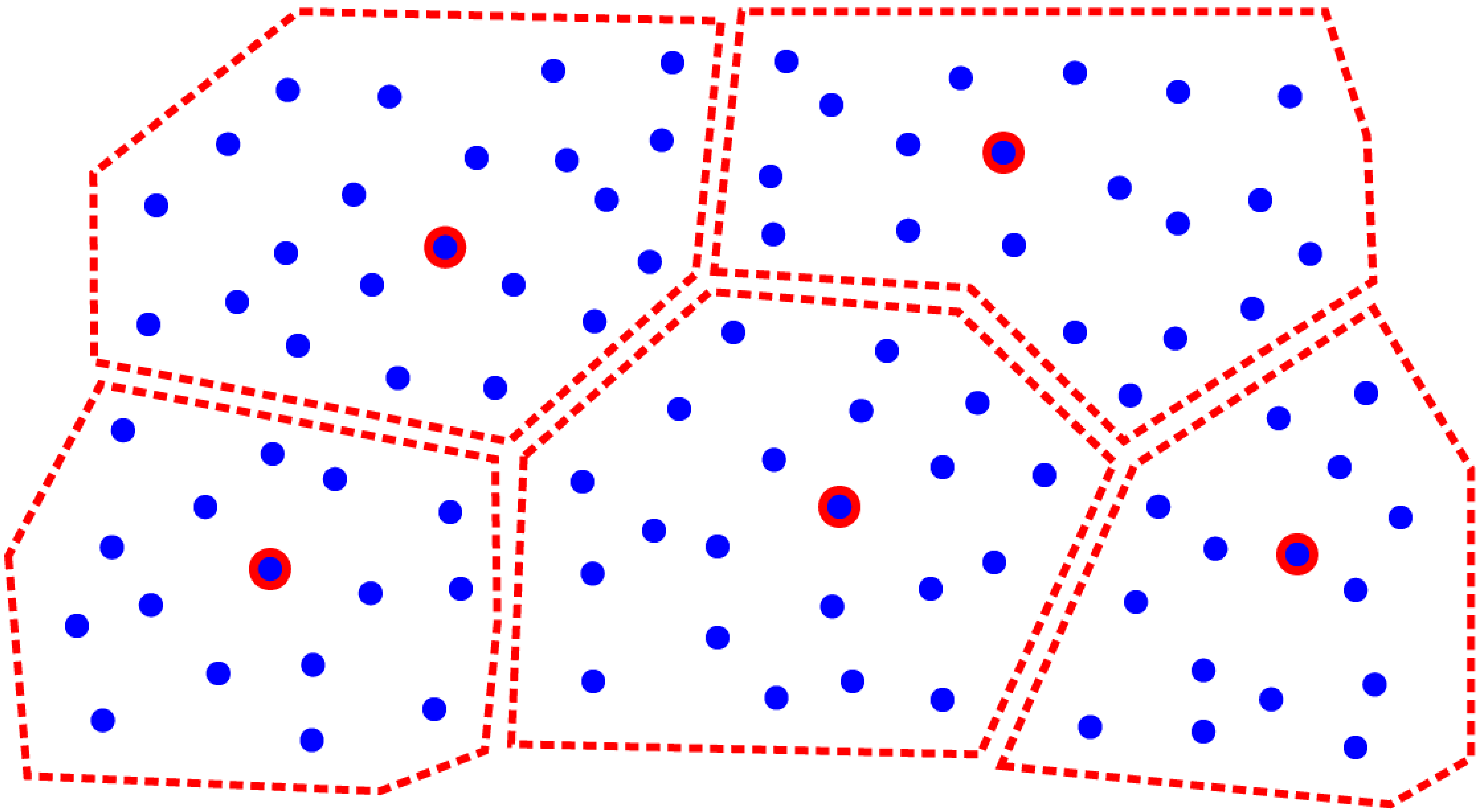
Safari Hierarchy Self-Organization

Drum nodes send limited propagation ***beacon*** floods:



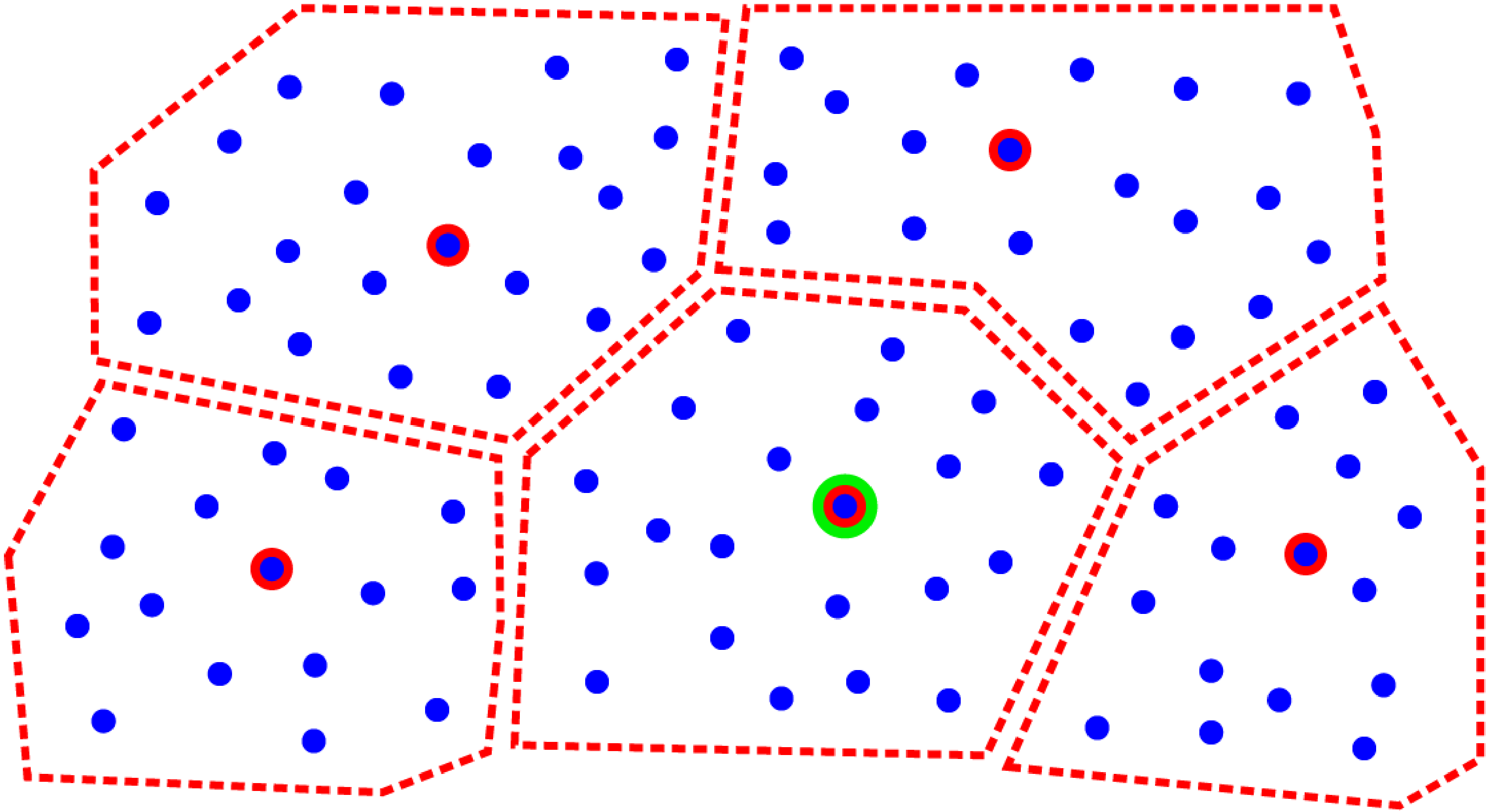
Safari Hierarchy Self-Organization

Other nodes associate with a drum to form ***cells***:



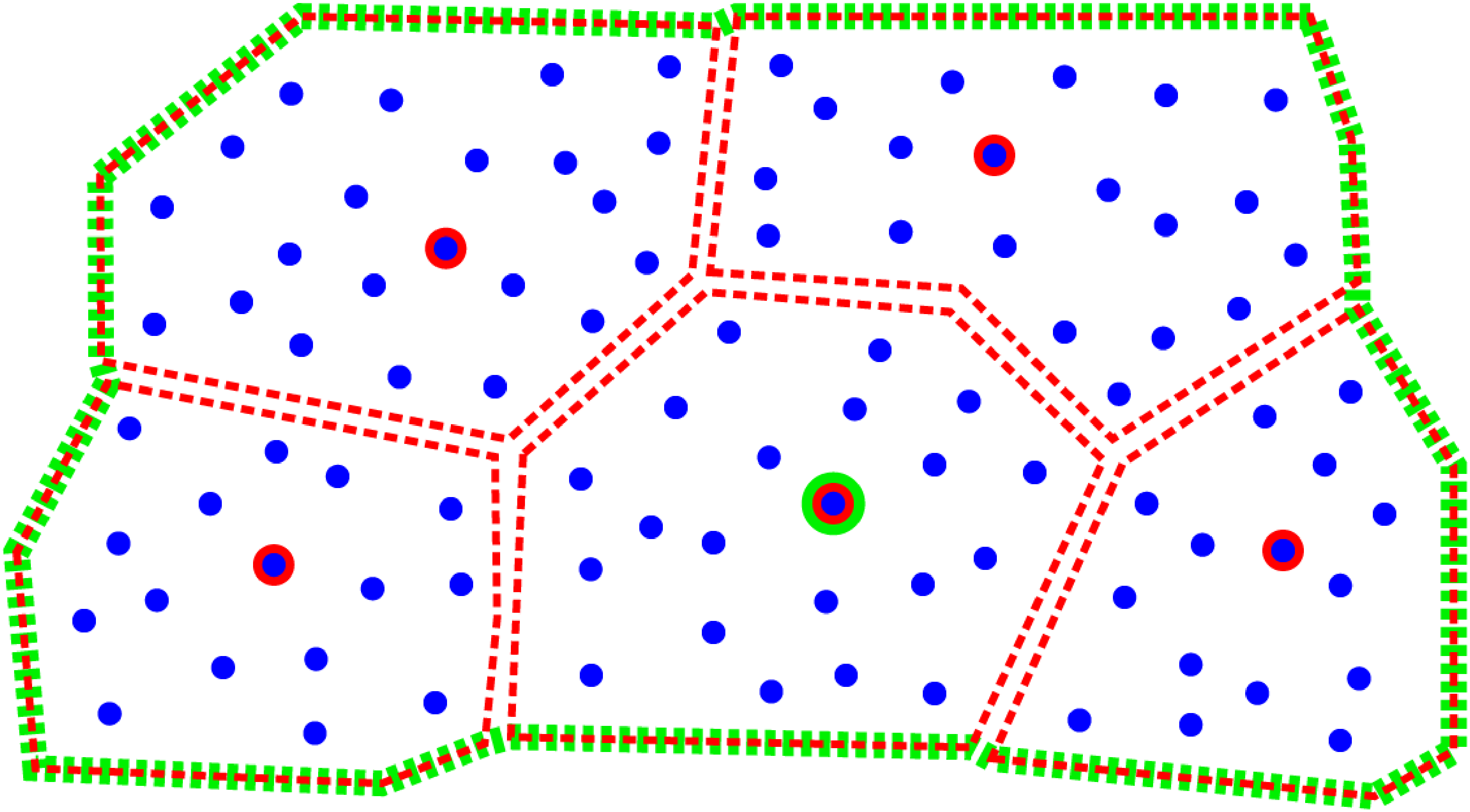
Safari Hierarchy Self-Organization

Drums at one level self-elect to become drum at next higher level:

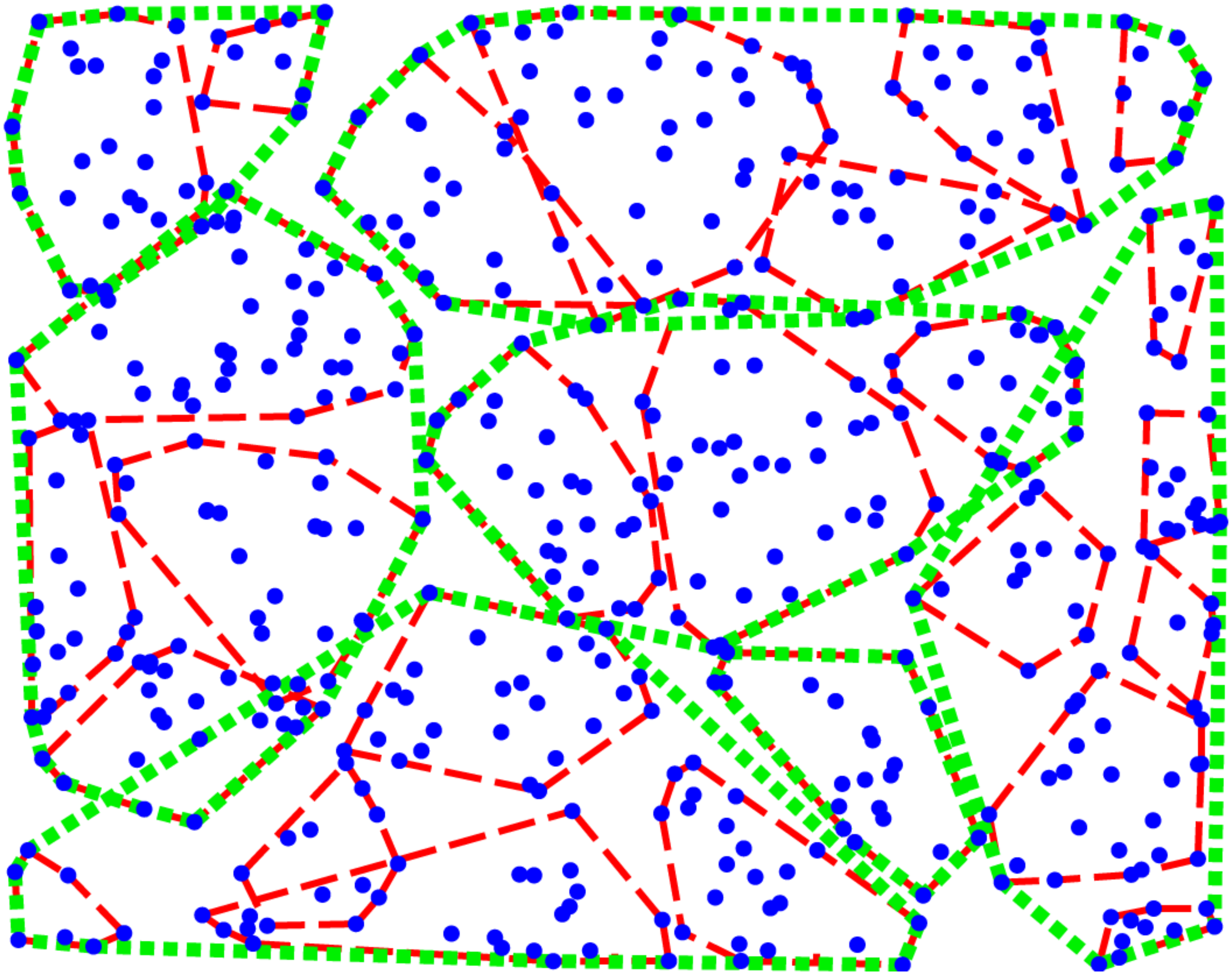


Safari Hierarchy Self-Organization

Forming cells at each higher level too:

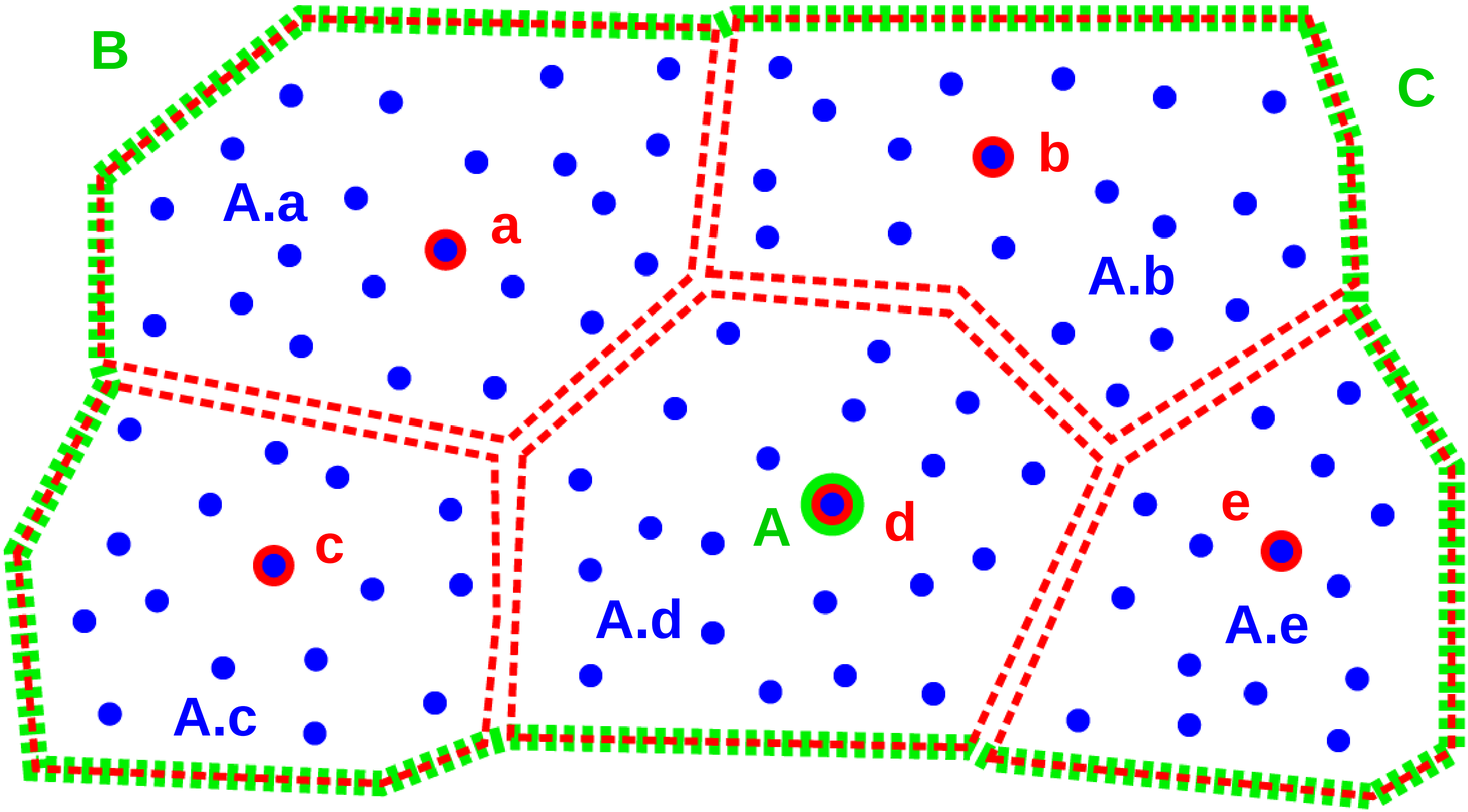


Simulation Example



Safari Coordinates

A node's coordinates = associated cell id at each hierarchy level



Safari Routing Overview

Destination node coordinates:

- Stored and looked up in Distributed Hash Table (DHT) using embedded peer-to-peer system

Hybrid routing protocol components:

- Route to destination cell following beacons (***proactive*** routing)
- Incremental local repair in this path (***reactive*** routing)
- Route to destination node within final cell (***reactive*** routing)

Routing table at a node:

- Remembers information from beacons received:
  - Coordinates of drum sending beacon
  - Previous hop node from which beacon received
  - Hop count back to the drum
  - Sequence number of most recent beacon from that drum

Proactive Inter-cell Routing

Range of beacons from a drum node:

- Nodes in the cell associated with that drum
- Nodes a few hops away, giving them a chance to join that cell
- Nodes in the containing cell one level up in the hierarchy

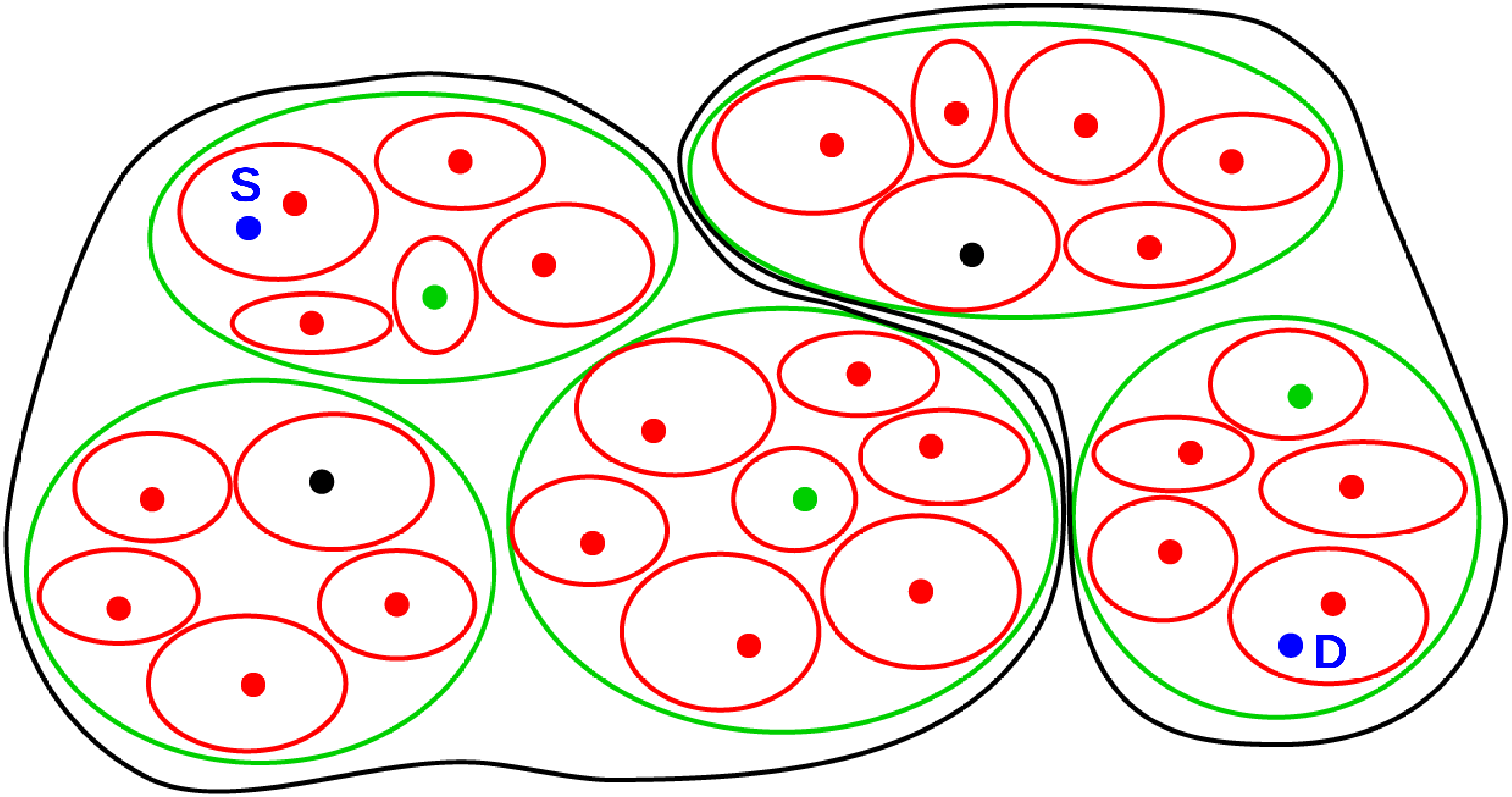
Routing table lookup algorithm:

- Nodes outside the cell hear the beacons:
  - Reasons described above
  - Wireless propagation allows nearby nodes to hear too
- Longest common prefix matching (similar to Internet!):
  - Compare your own coordinates to each entry in routing table
  - As soon as packet comes to node with more detailed table entry, packet starts following lower in routing hierarchy

Packets are routed ***toward*** drums, <u>not</u> ***through*** drums!

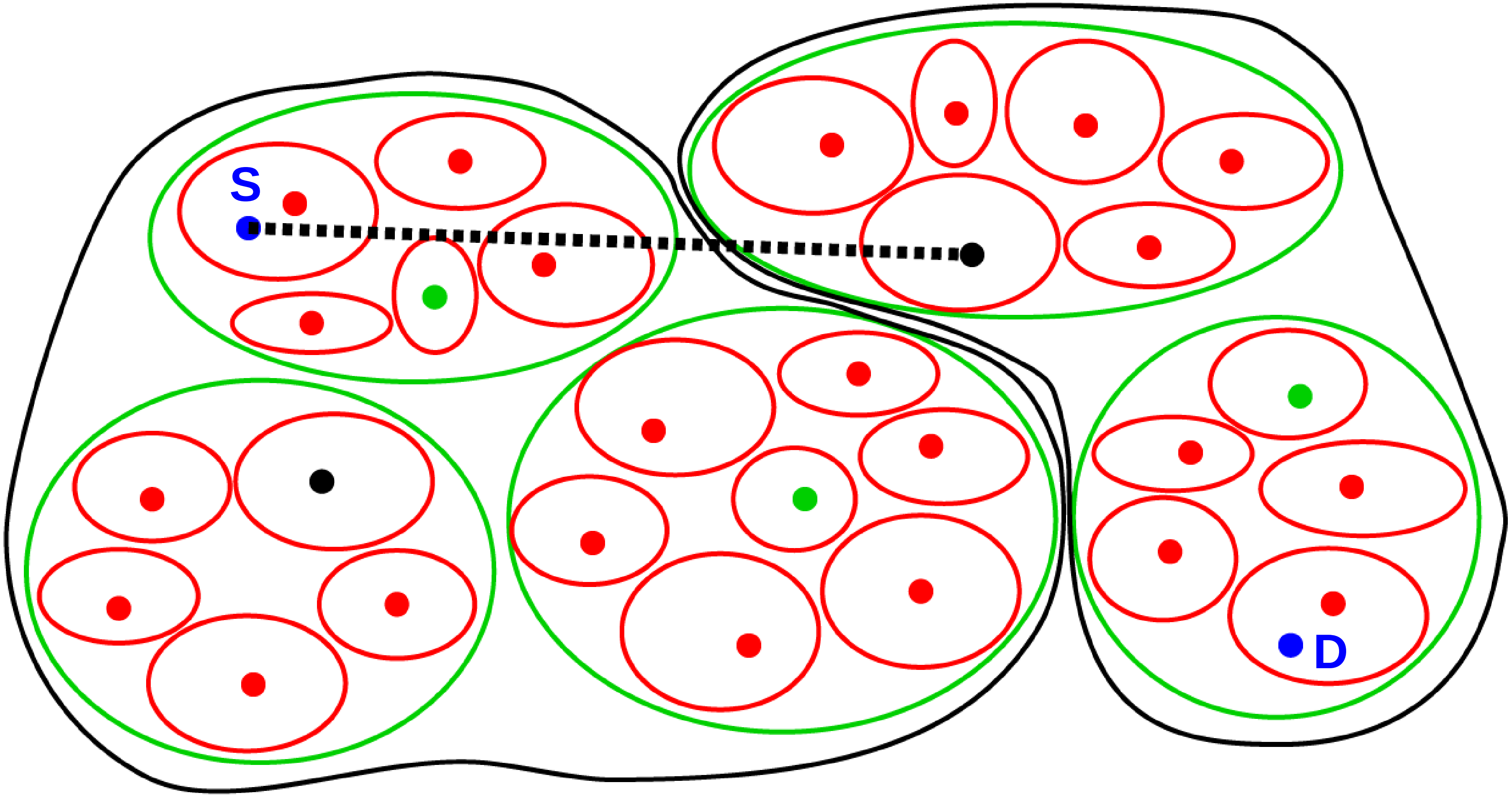
Routing Example

Source node S is sending a packet to destination node D:



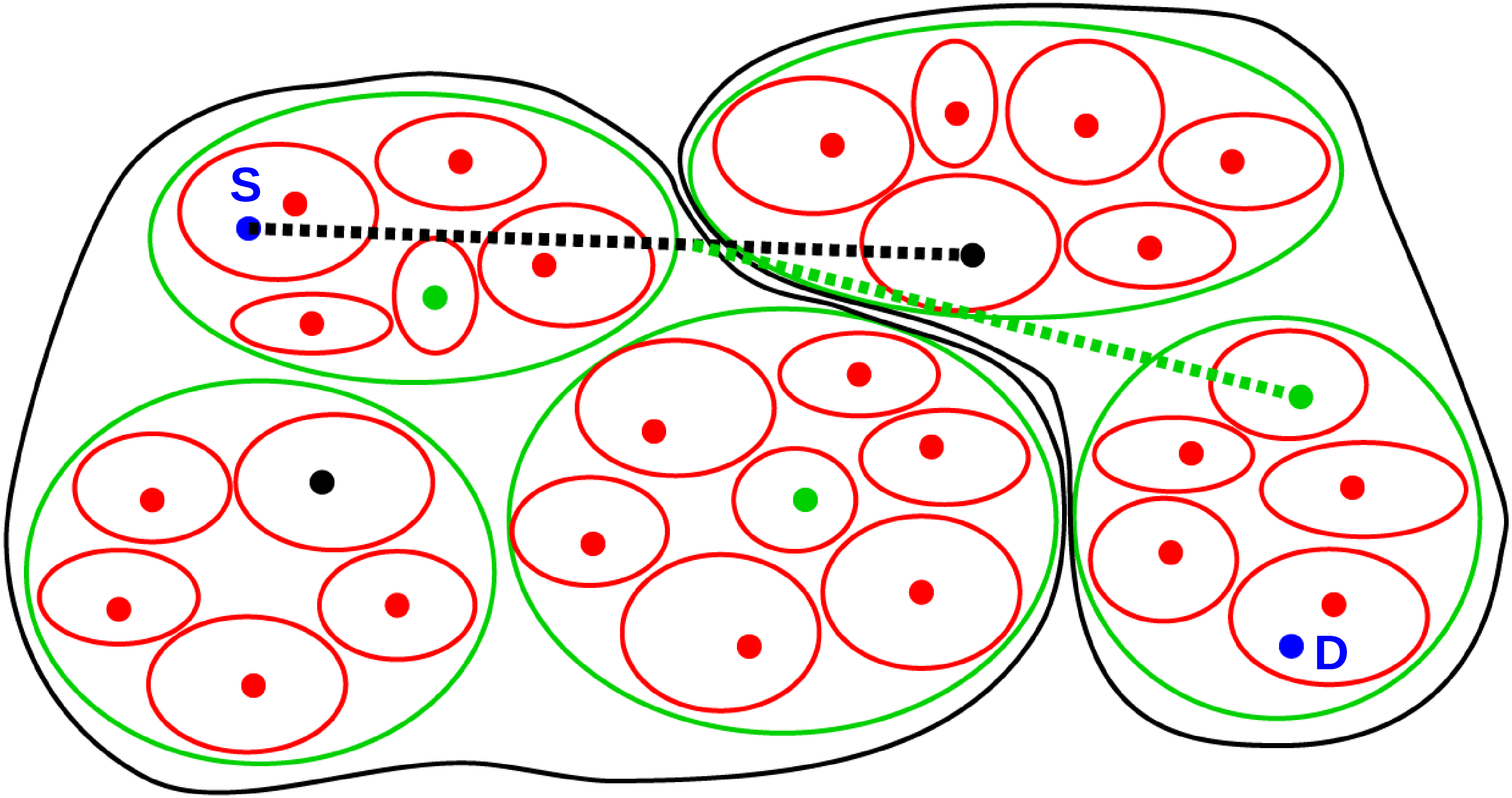
Routing Example

Follow beacon path ***toward*** level 3 cell in which D is located:



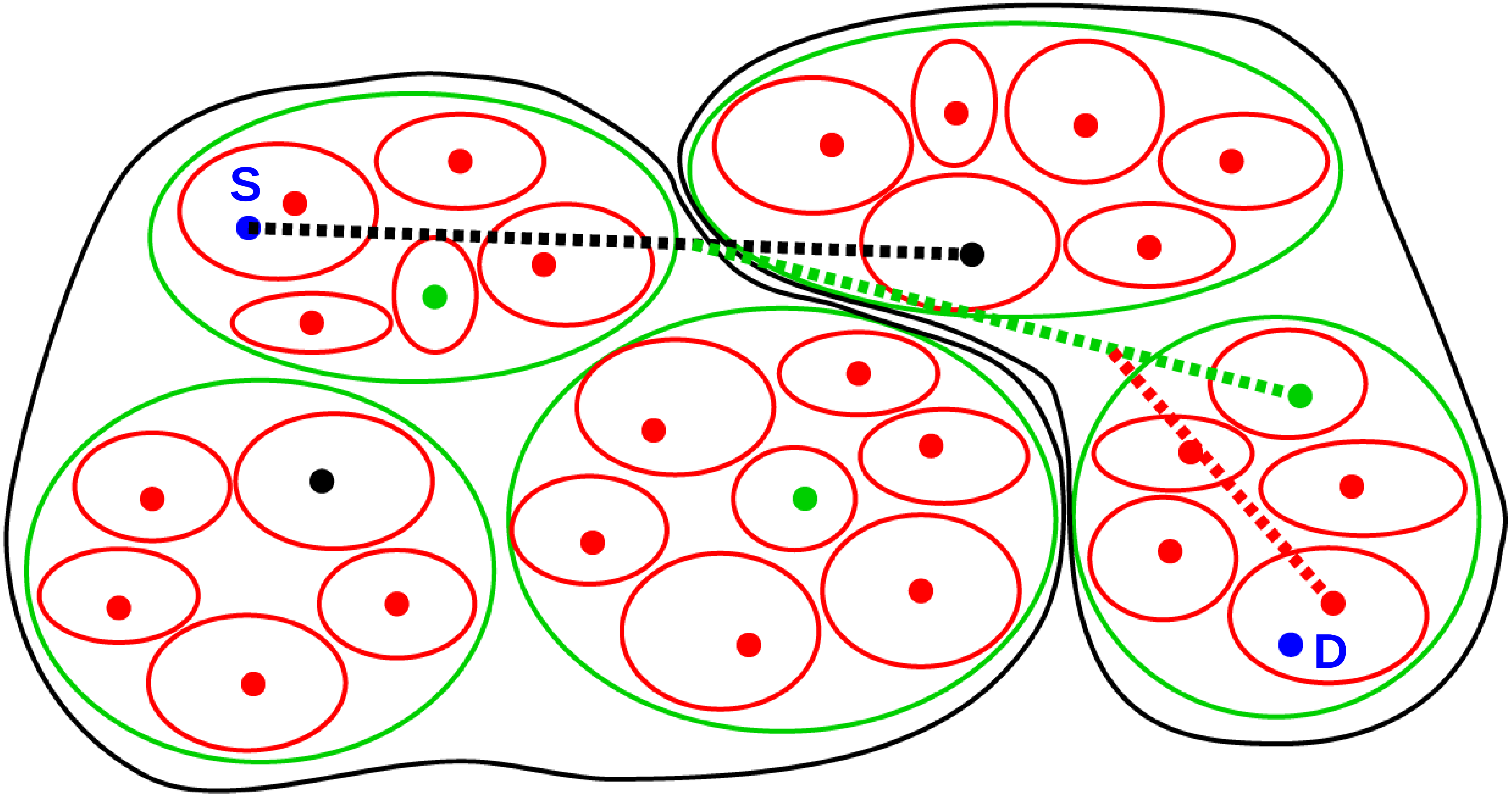
Routing Example

Follow beacon path ***toward*** level 2 cell in which D is located:



Routing Example

Follow beacon path ***toward*** level 1 cell in which D is located:



Reactive Intra-cell Routing

Dynamic Source Routing protocol (DSR):

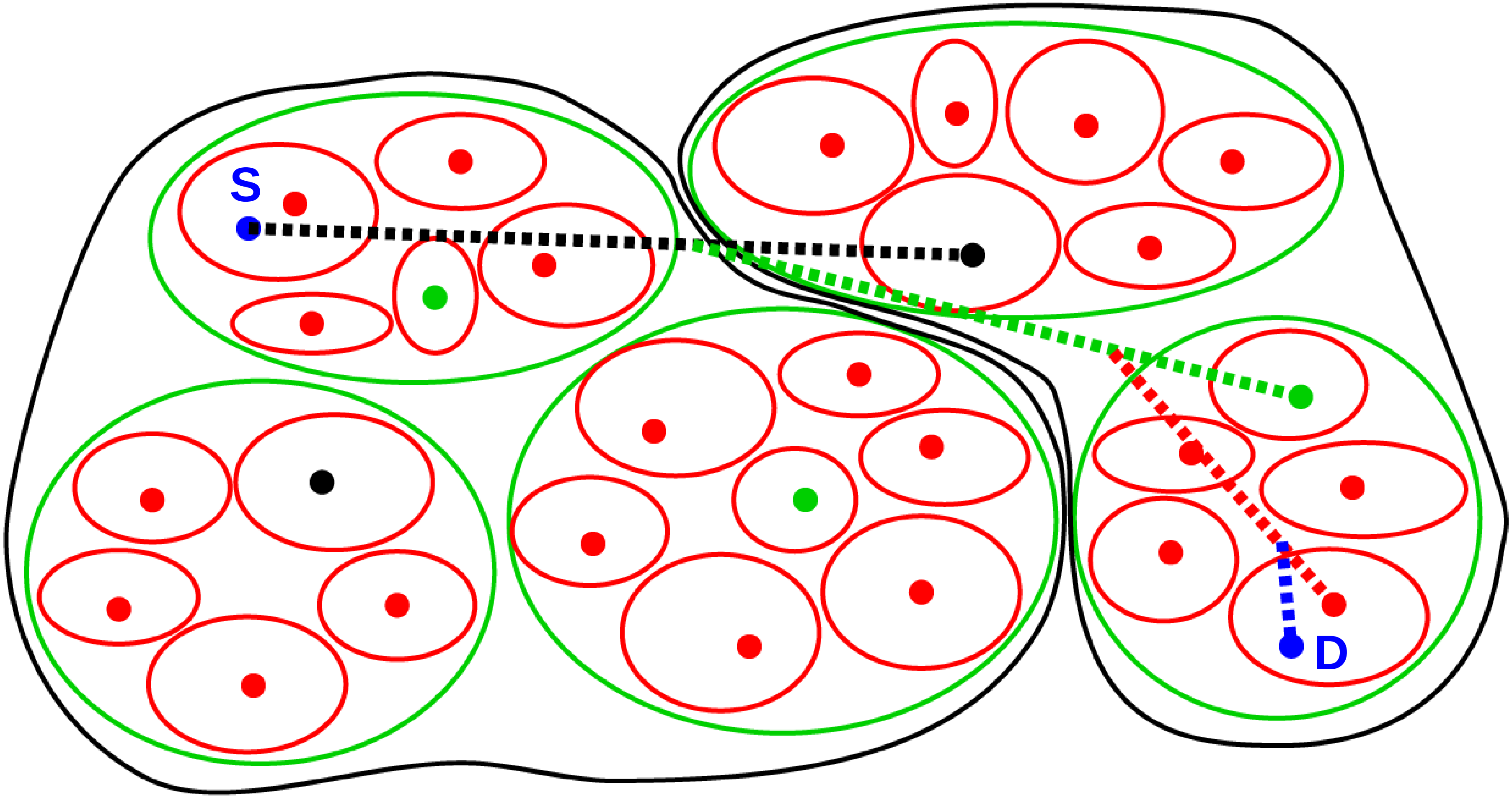
- Discovers routes only as needed, on demand (Route Discovery)
- Detects when links being used for routing are broken, on demand only as they are used (Route Maintenance)
- Very low overhead, scalable to mobility and traffic needs
- ***Zero*** overhead until new route is needed

Using DSR in Safari routing:

- DSR originally designed for small or medium sized networks
- Safari intended to scale to ***much*** larger sizes
- Safari uses DSR only within destination fundamental cell
- Size of fundamental cells created by Safari balance two things:
  - Small enough for very easy efficient reactive routing
  - Large enough to minimize when nodes move to new cells

Routing Example

On-demand DSR routing to destination node D:



Emerging New Areas of Ad Hoc Networking

- ***Sensor networking:***
  - Nodes are generally stationary
  - Long lifetime (power conservation) is most important
- ***Mesh networking:***
  - Shared Internet access, neighborhood gaming, medical and emergency response, neighborhood watch, shared community resource, distributed backup
- ***Vehicular ad hoc networking:***
  - Limited/predicable mobility, power availability
  - QoS is important (emergency notification), traffic management, general network access
- ***Hybrid infrastructure ad hoc networking:***
  - Route to nearest base station or direct if closer
  - Desire fairness independent of hop count to base station

Conclusion

From The Economist Magazine, June 20, 2002:

- Four ***disruptive technologies*** are emerging that promise to render not only the next wave of so-called 3G wireless networks irrelevant, but possibly even their 4G successors
- Ad hoc networking will create more scope for "mom and pop" network operators and free community networks, all stitched together in a casual, ever-shifting web.
- Network operators will still be needed to carry long-haul traffic, but their role could become less (rather than more) important in future. In the process, the entire structure of the industry could shift from a top-down approach to one that is organised from the bottom up. There are already signs of this happening in the emerging area of commercial WI-FI networks, which allow individuals to club together to form a larger network.