Spotlight: Exploiting Smart Antennas for Future Wireless Networks

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Internet Edge

- Internet continues to extend over wireless
  - 2005 survey - 100,000 WiFi hotspots
  - Projection - 167,000 by 2008
  - User base - 75 million
- Mesh networks further extendig WLANs
  - Spreading in developing regions
    - VoIP at Mahavilachchiya, Sri Lanka: no telephone till date
    - Digital Gangetic Project, India
    - Rural wireless, China
    - Wireless Ghana
    - Mesa Grande Project, Southern California

Internet Edge

- Wireless growth in various other forms
  - WiMAX
  - Sensor Networks (motes and mobile phones)
  - RFID Networks
  - Body Area Networks
  - Vehicular Networks
  - Delay and Disconnection Tolerant Networks
  - …

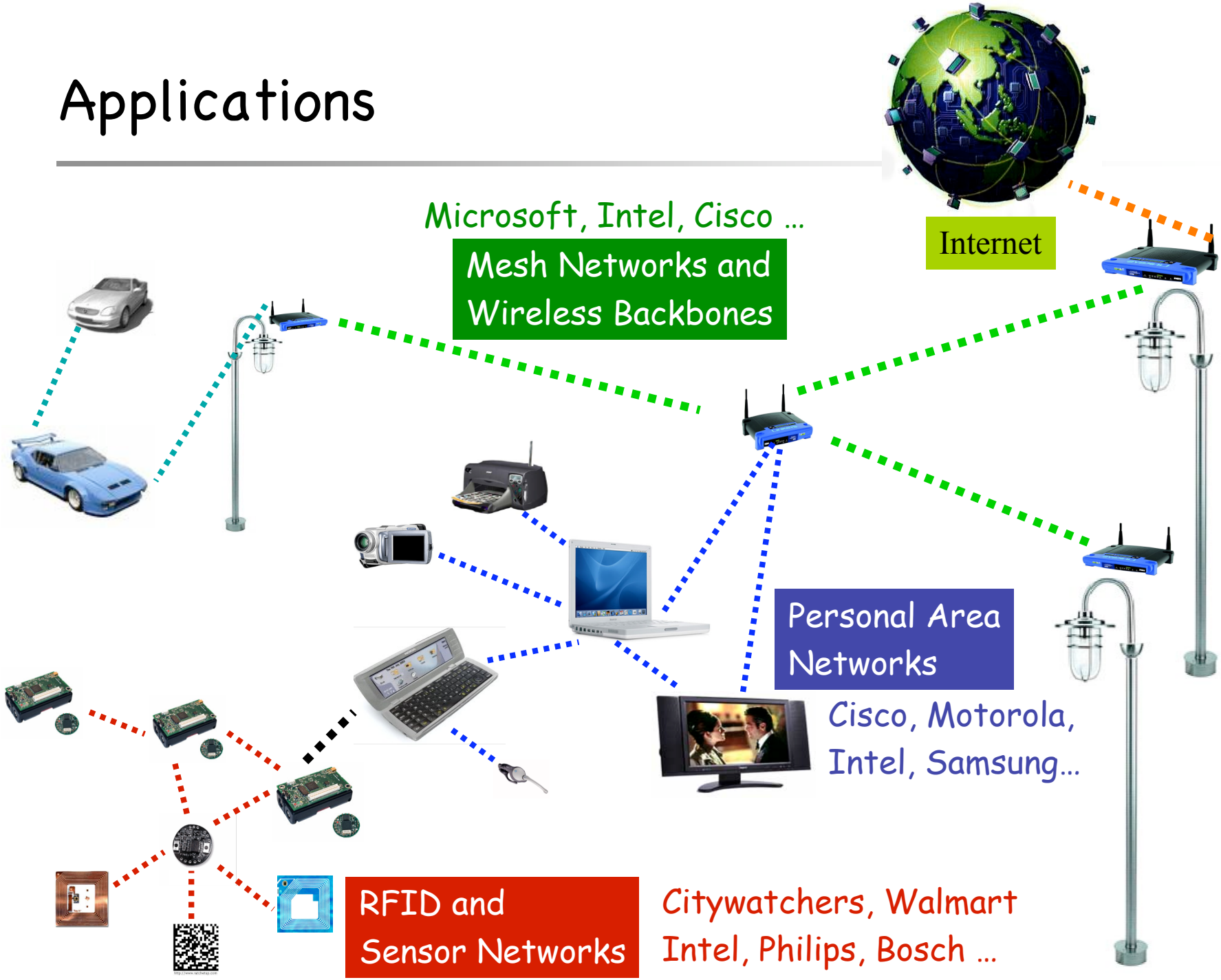
Surveys and analysis unanimous on one front

"Tremendous growth till 2012 and beyond"

The Success Metric:

"Take wireless for granted, like electricity"

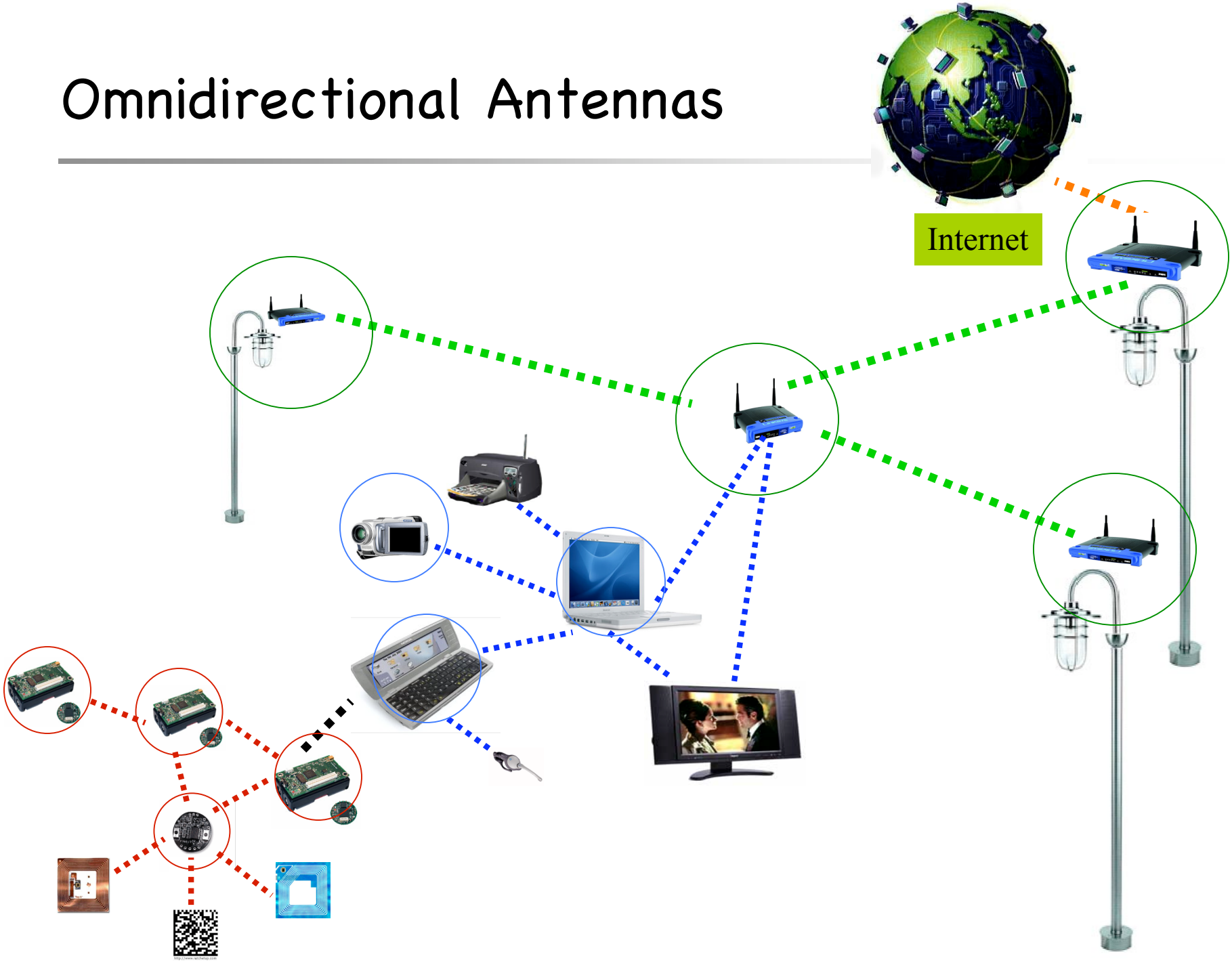
Applications



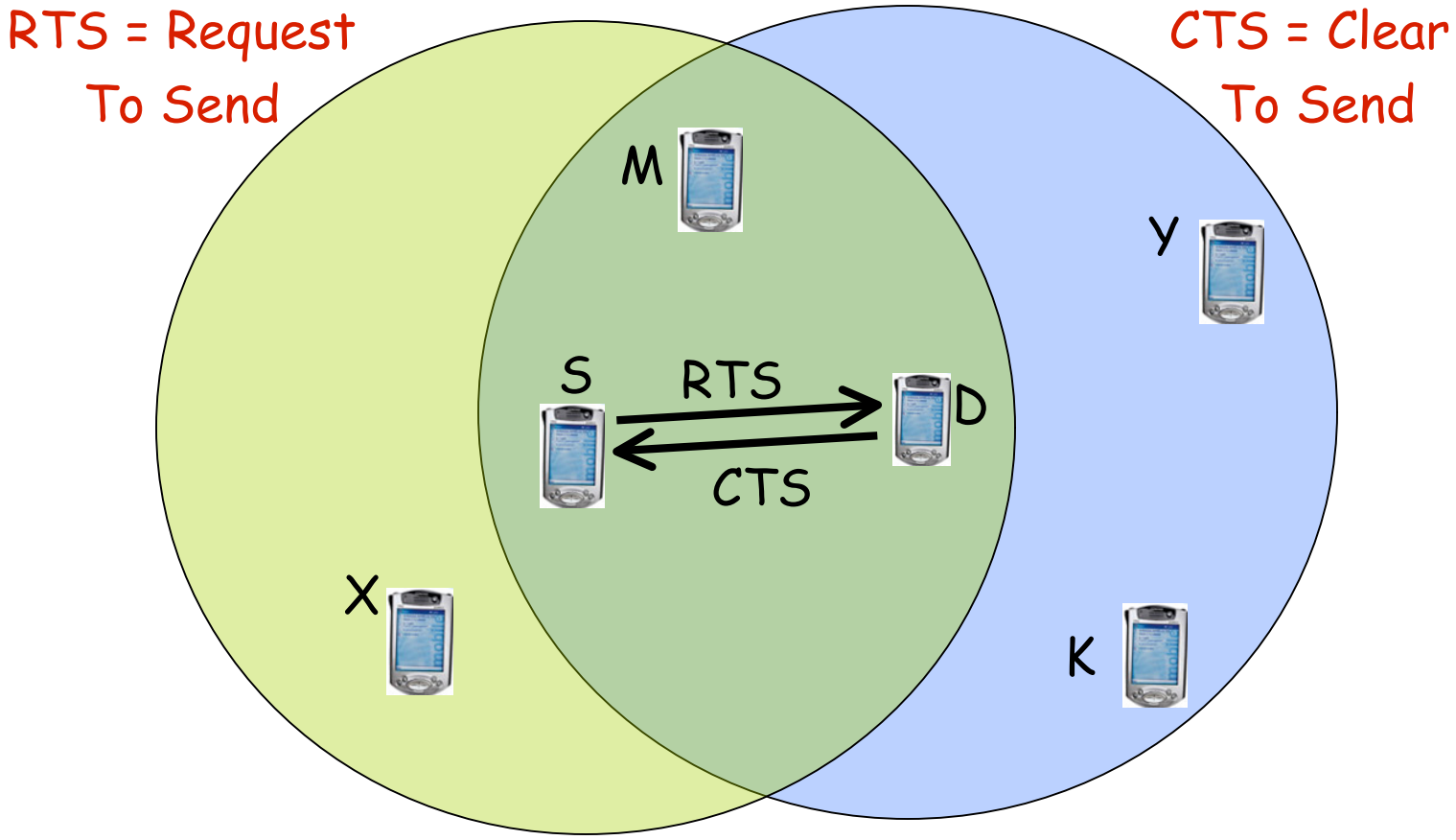
Protocol Design

- Numerous challenges
  - Connectivity (nodes can be mobile)
  - Capacity (increasing demand)
  - Reliability (channels fluctuate)
  - Security
  - QoS …
- Active research in progress
  - Many protocols already/being designed
- Till recent past, one commonality …

Omnidirectional Antennas



IEEE 802.11 with Omni Antenna



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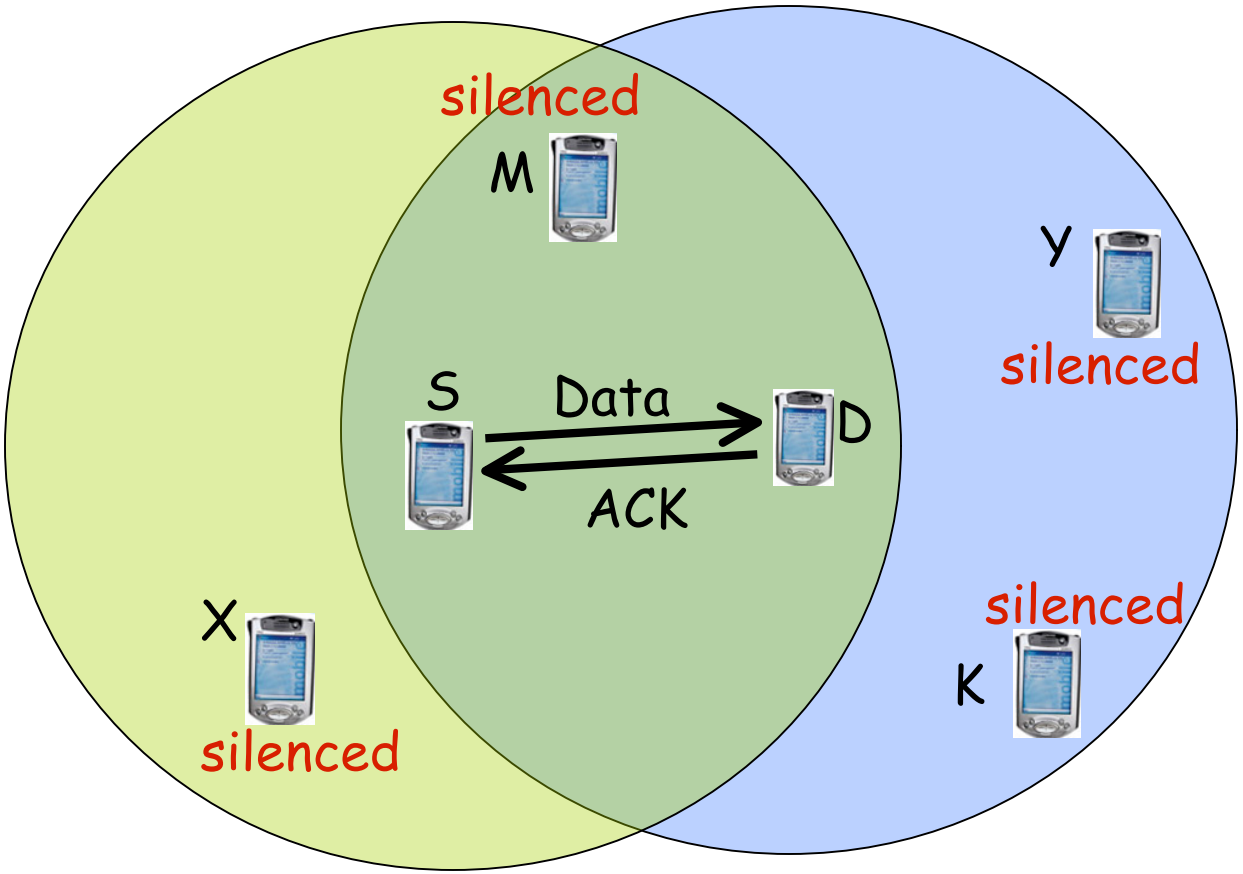

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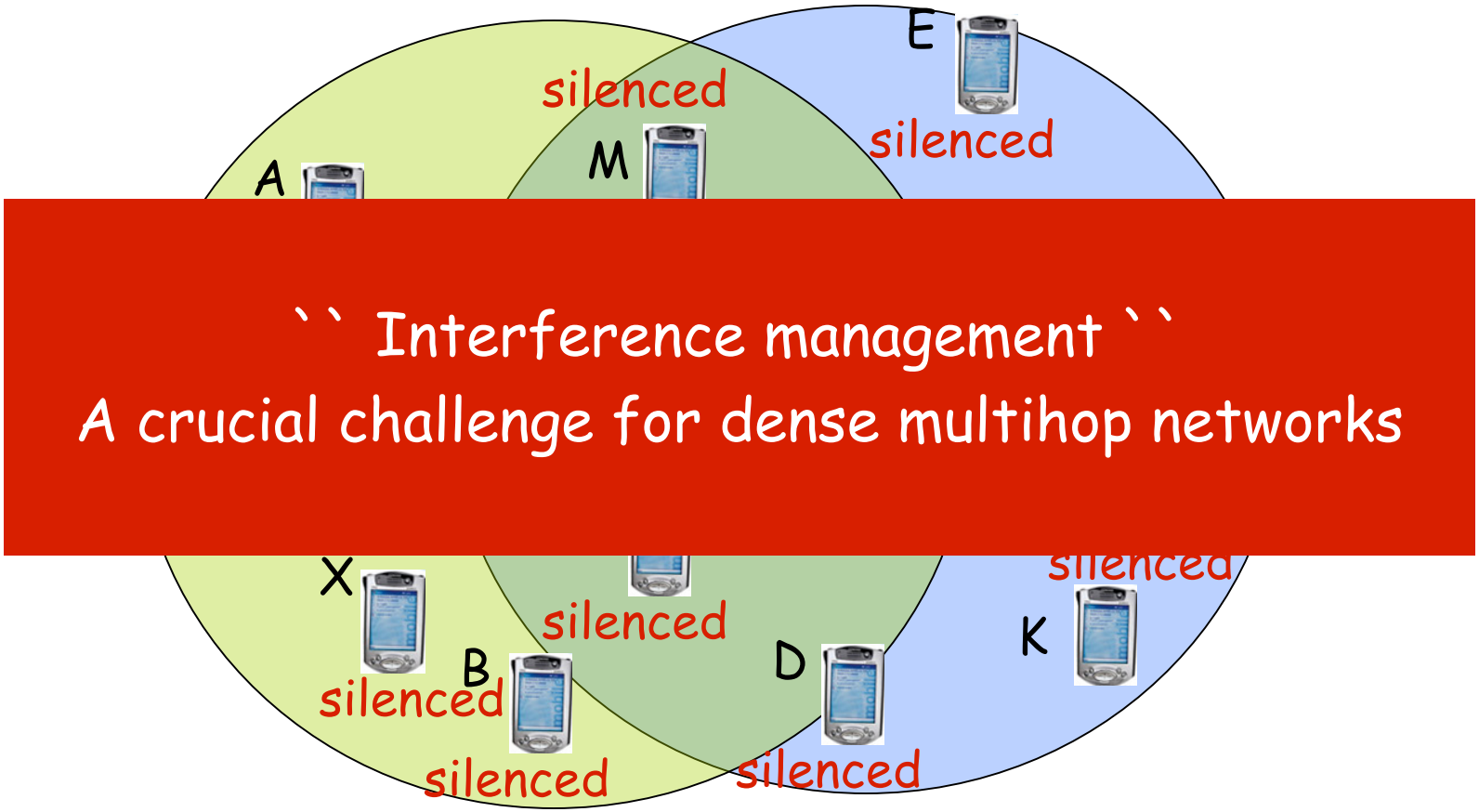


`` Interference management ``

A crucial challenge for dense multihop networks

Managing Interference

- Several approaches
  - Dividing network into different channels
  - Power control
  - Rate Control …

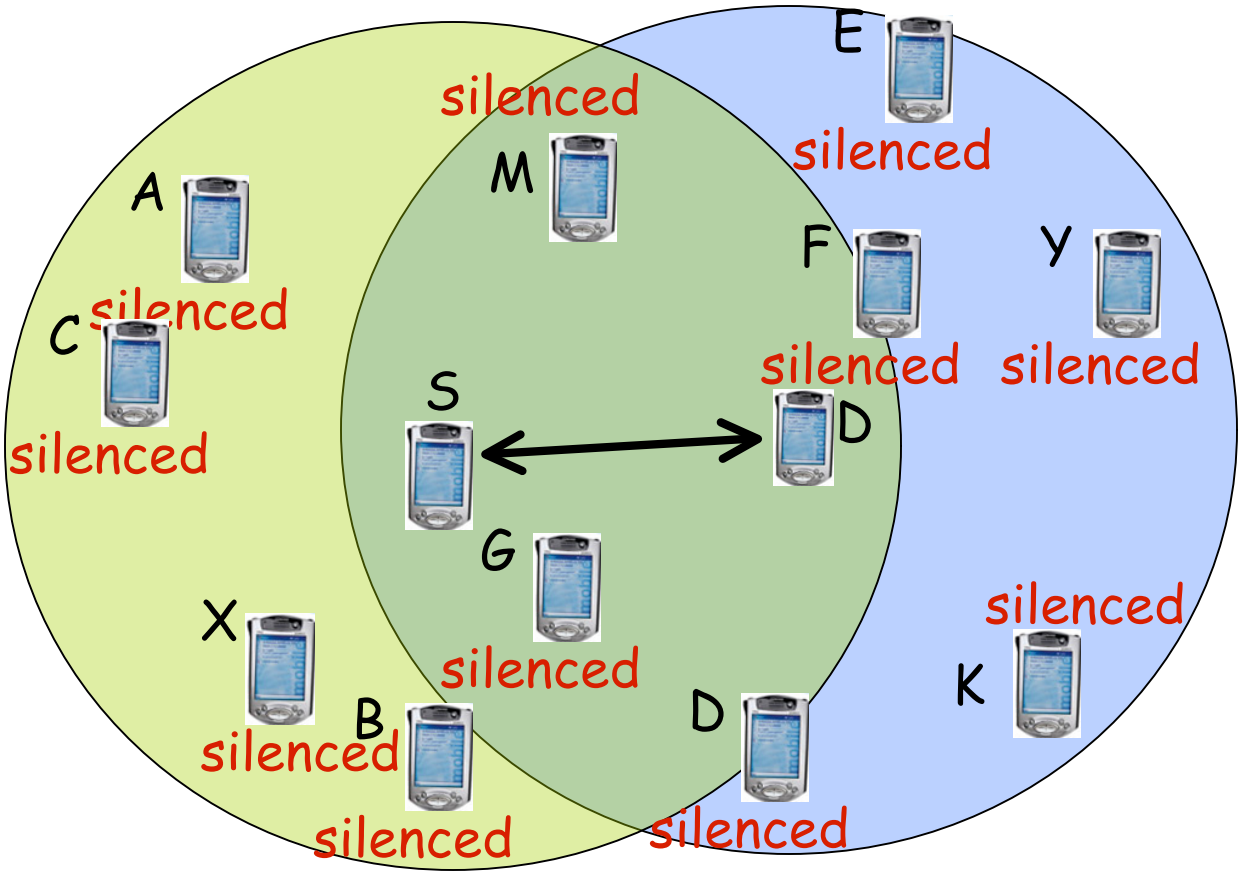
Our Approach …

Exploiting antenna capabilities to improve the performance of wireless multihop networks

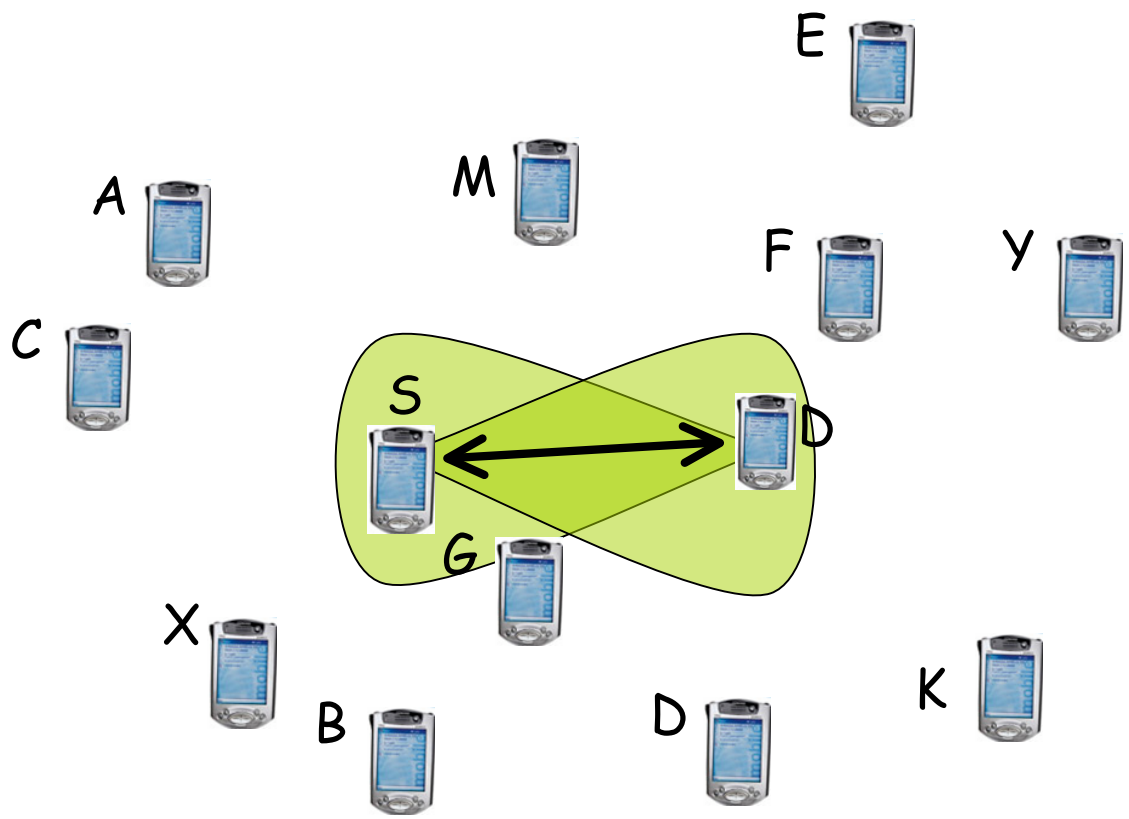
Spectrum of Capabilities

- » Switched Beam Antennas
- » Reconfigurable Antennas
- » MIMO Beamforming
- » MIMO Spatial Multiplexing
- » …

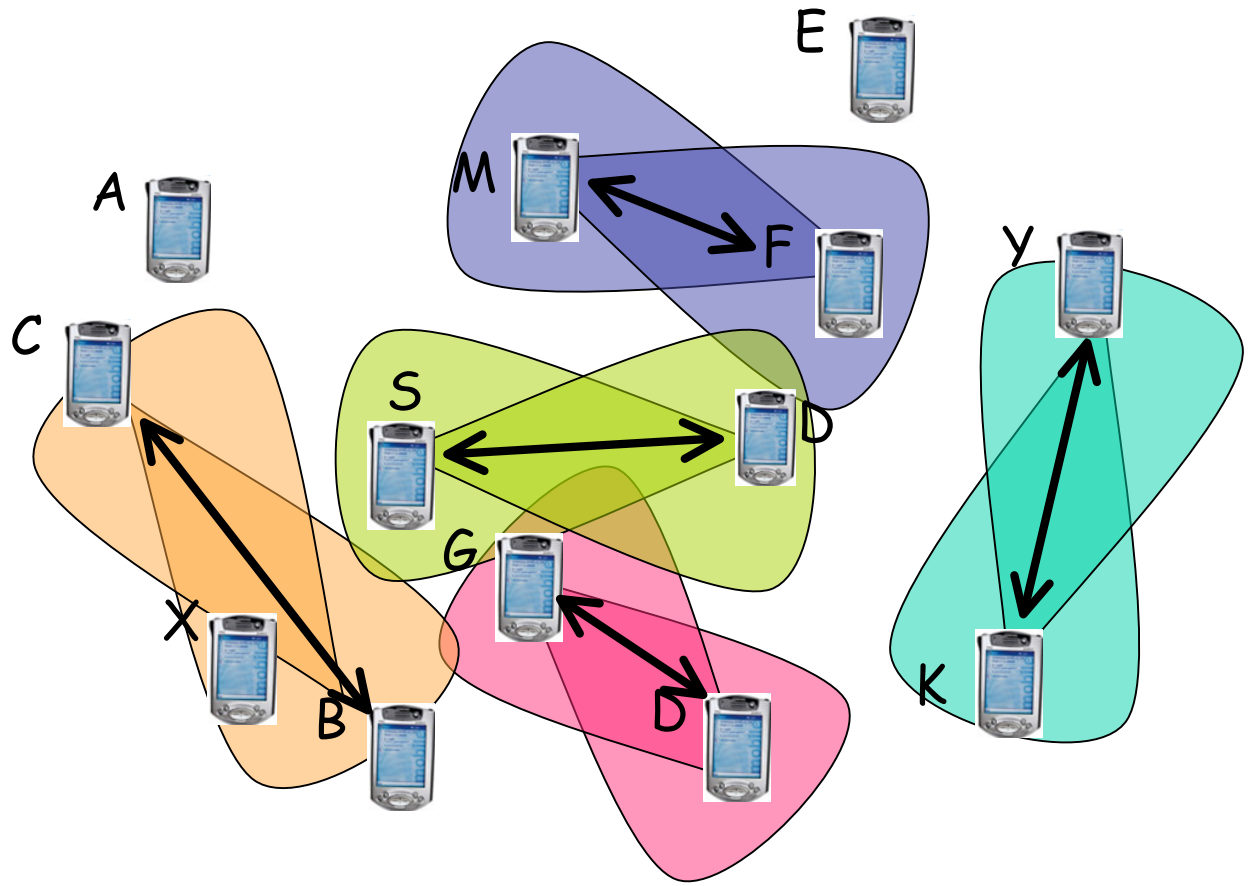
From Omni Antennas …



To Beamforming Antennas



To Beamforming Antennas



Outline / Contribution

- Antenna Systems → A closer look
- New challenges with beamforming antennas
- Design of MAC and Routing protocols
  - MMAC, ToneDMAC, CaDMAC
  - DDSR, CaRP
  - Cross-Layer protocols – Anycasting
  - Improved understanding of theoretical capacity
  - Security
- Experiment with prototype testbed

Commercial Antennas …

- Signal Processing + Antenna Design + hi freq
  - Several types of beamforming antennas

- Many becoming commercially available
  - Fidelity Comtech (Phocus Array Antennas)
  - Paratek (DRWin scanning smart antennas)
  - Motia Inc. (Javelin appliqué to 802.11 cards)
  - CalAmps (DirectedAP digital beamforming)
  - Belkin (Pre-N smart antenna router – Airgo tech.)
  - Tantivy Communications (switching < 100 nanosec)

Electronic Beamforming Antenna [ATR Japan]

- Higher frequency, Smaller size, Lower cost
  - Capable of Omnidirectional mode and Directional mode

Switched and Array Antennas

- On poletop or vehicles
  - Antennas bigger
  - No power constraint

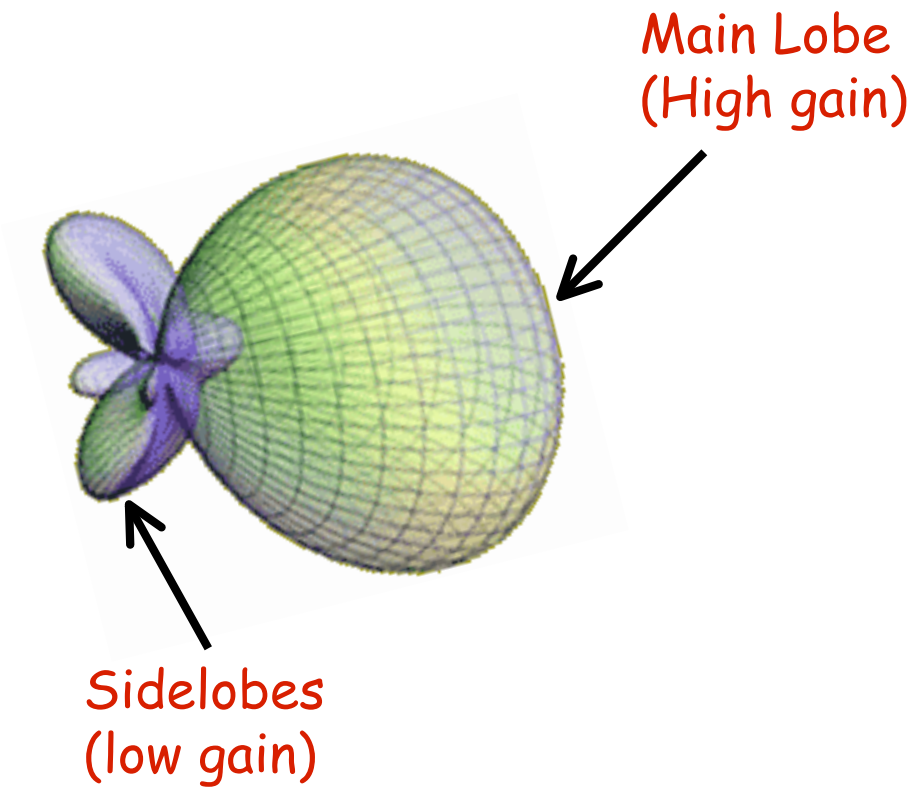
Beamforming Antenna Abstraction

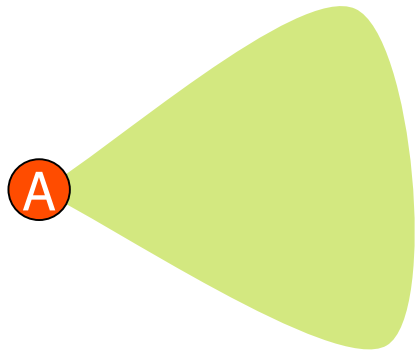
- 3 Possible antenna modes
  - Omnidirectional mode
  - Single Beam mode
  - Multi-Beam mode

- Higher Layer protocols select
  - Antenna Mode
  - Direction of Beam

Antenna Beam

- Energy radiated toward desired direction



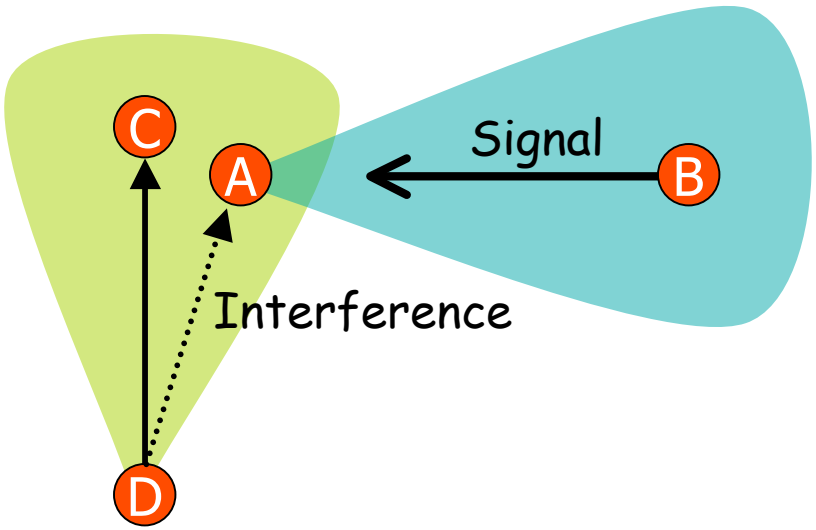


Pictorial Model

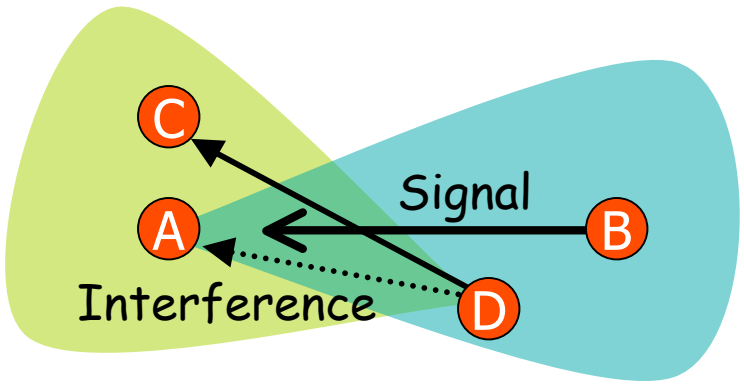
Courtesy of Fidelity - 43 degree high gain beam

Directional Reception

- Directional reception = Spatial filtering
  - Interference along straight line joining interferer and receiver



No Collision at A



Collision at A

Will attaching such antennas at the radio layer yield most of the benefits ?

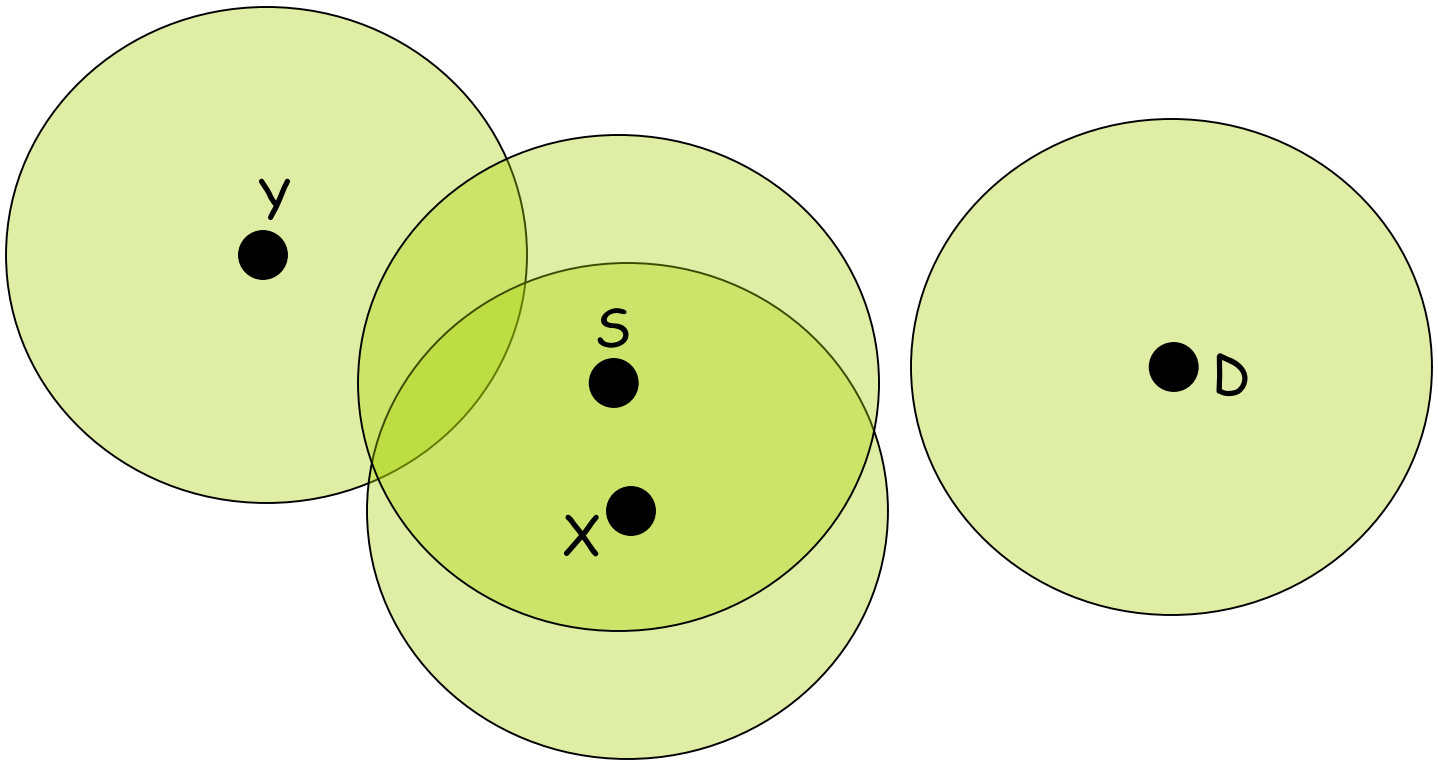
Or

Is there need for higher layer protocol support ?

We design a simple baseline MAC protocol
(a directional version of 802.11)

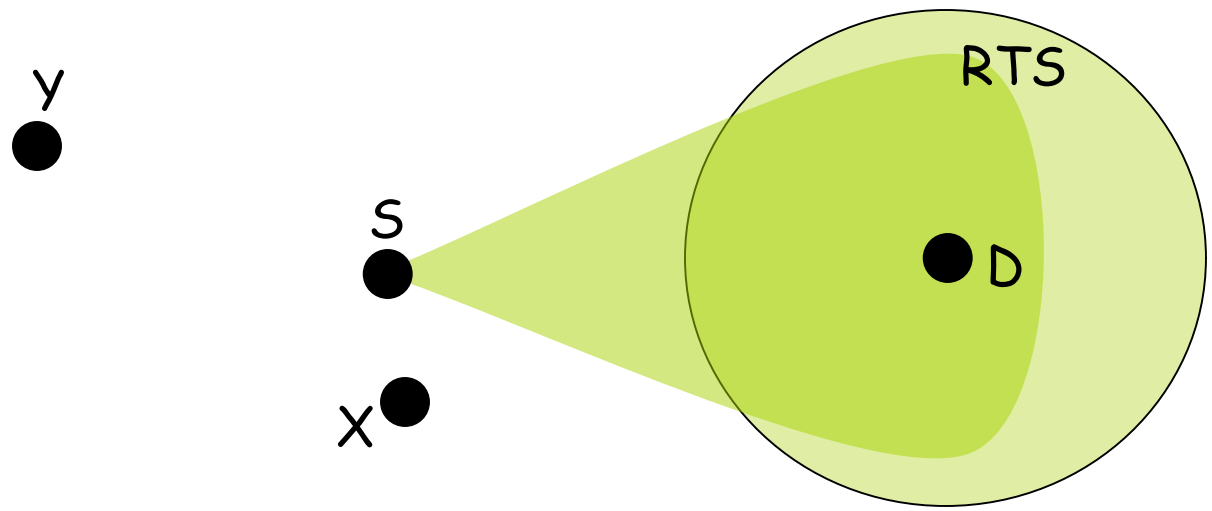
We call this protocol DMAC and investigate
its behavior through simulation

DMAC Example



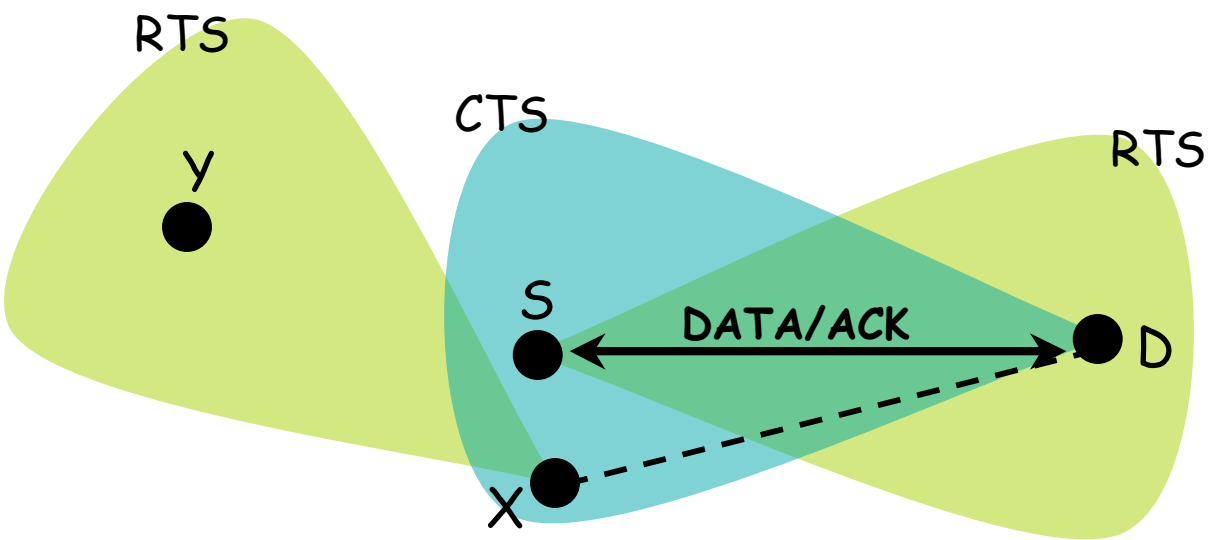
- Remain omni while idle
  - Nodes cannot predict who will trasmit to it

DMAC Example



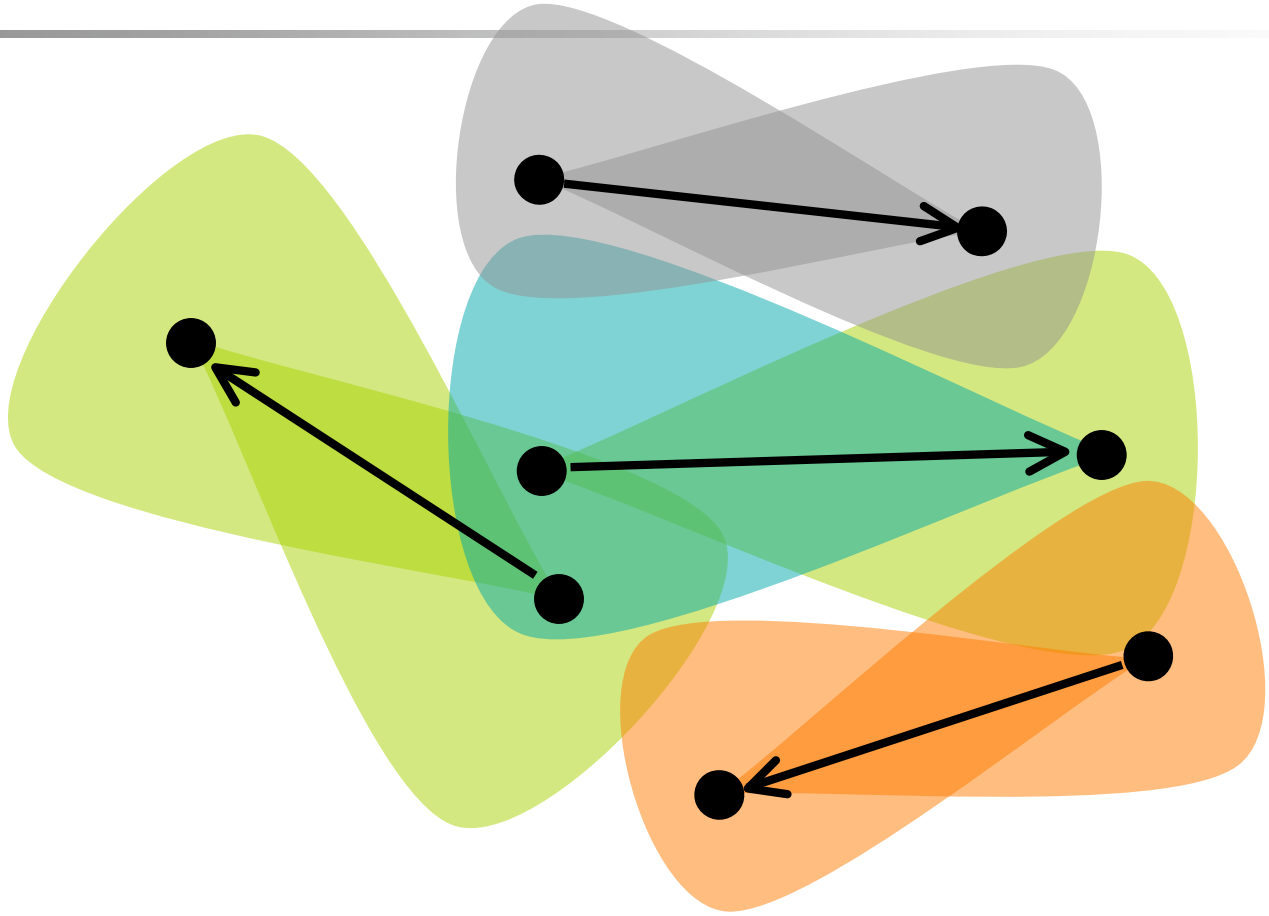
- Assume S knows direction of D

DMAC Example



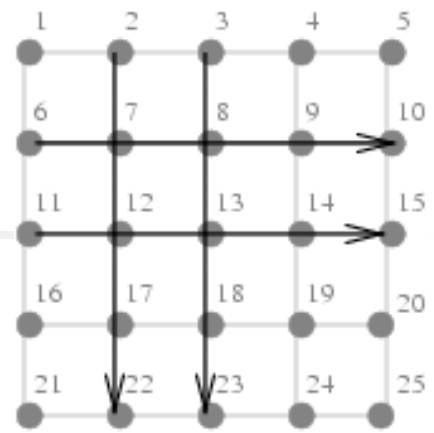
X silenced … but only toward direction of D

Intuitively



Performance benefits appear obvious

However …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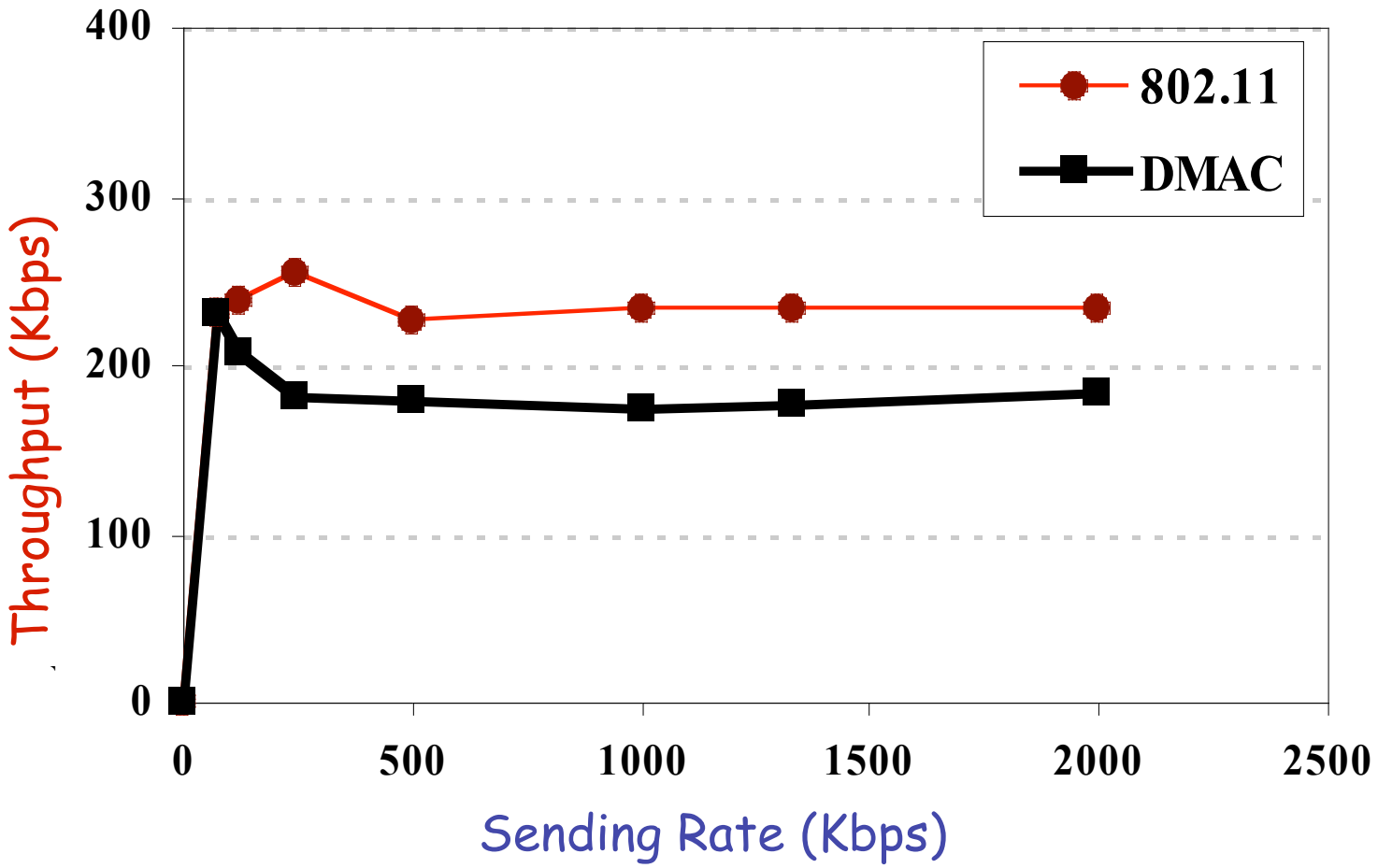

802.11
DMAC
Throughput (Kbps)
400
300
200
100
0
0
500
1000
1500
2000
2500
Sending Rate (Kbps)

Clearly, attaching sophisticated antenna hardware is not sufficient

Simulation traces revealed various new challenges

Motivates higher layer protocol design

Outline / Contribution

- Antenna Systems → A closer look
- New challenges with beamforming antennas
- Design of MAC and Routing protocols
  - MMAC, ToneDMAC, CaDMAC
  - DDSR, CaRP
  - Cross-Layer protocols – Anycasting
  - Improved understanding of theoretical capacity
- Experiment with prototype testbed

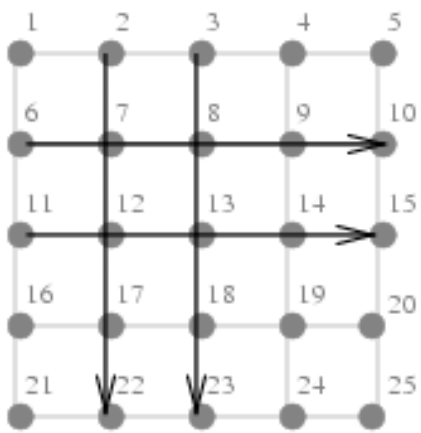
New Challenges [Mobicom 02]

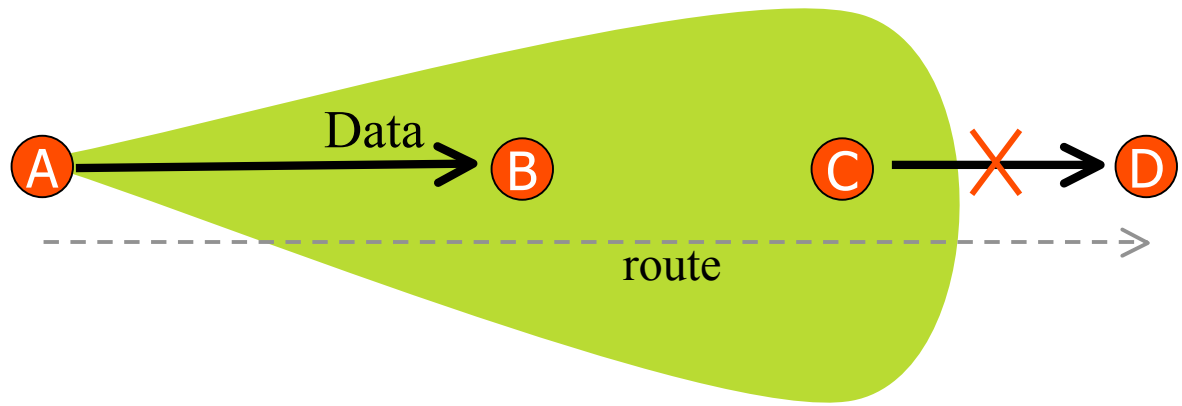
Self Interference

with Directional MAC

Unutilized Range [Best Paper, PWC 03]

- Longer range causes interference downstream
  - Offsets benefits





  - Network layer needs to utilize the long range
  - Or, MAC protocol needs to reduce transmit power

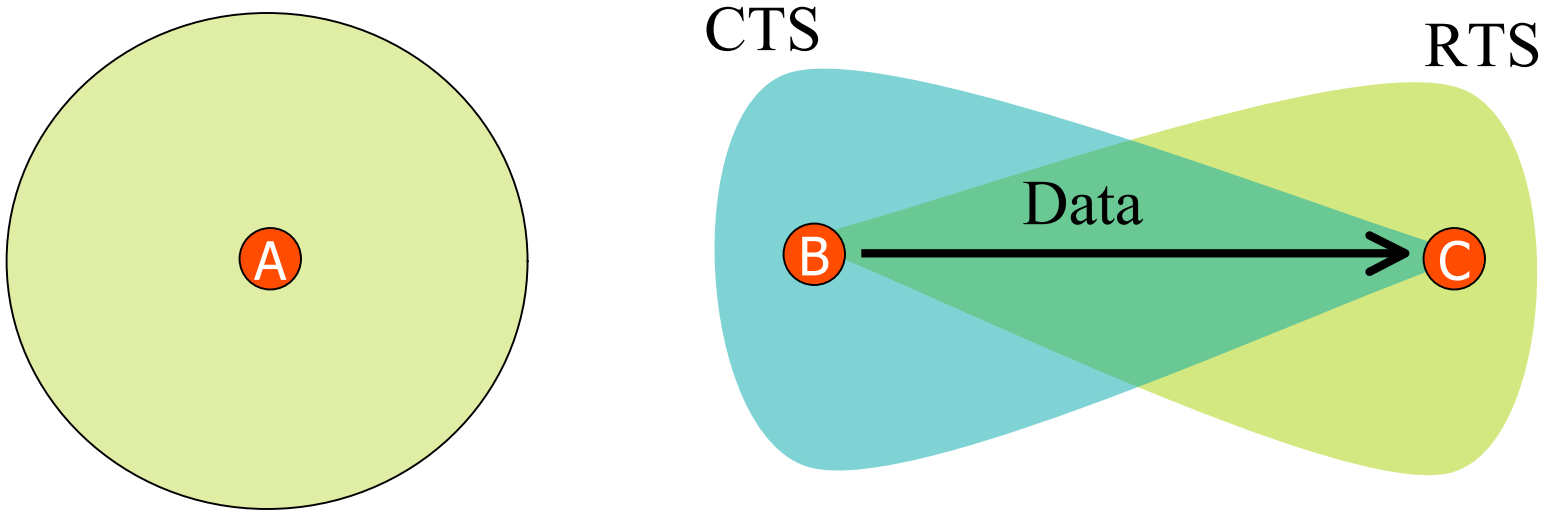
New Challenges II …

New Hidden Terminal Problems

with Directional MAC

New Hidden Terminal Problem [IEEE TMC]

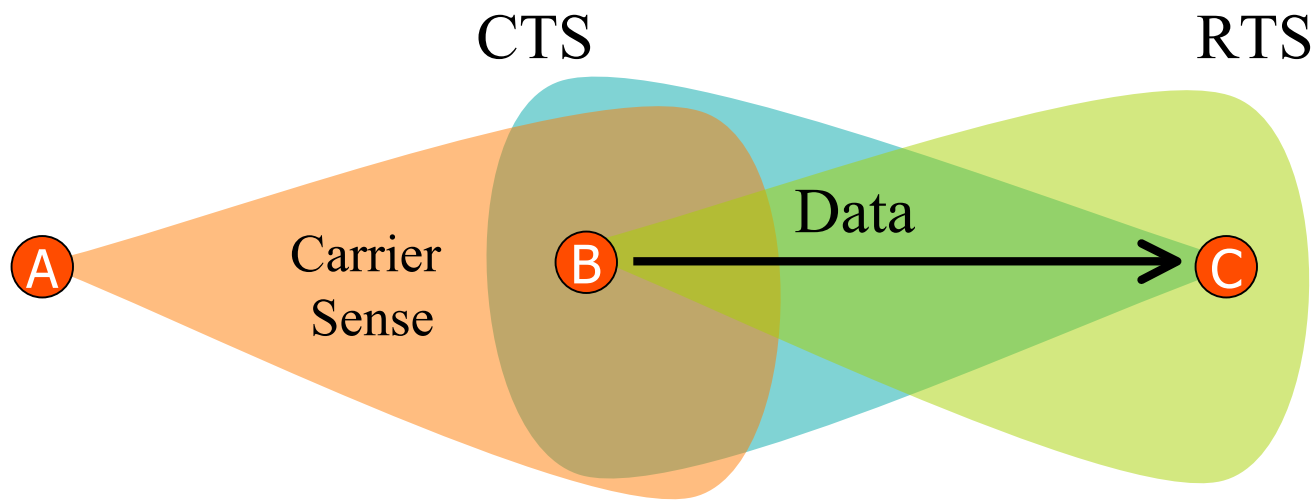
- Due to gain asymmetry



- Node A may not receive CTS from C
  - i.e., A might be out of DO-range from C

New Hidden Terminal Problem

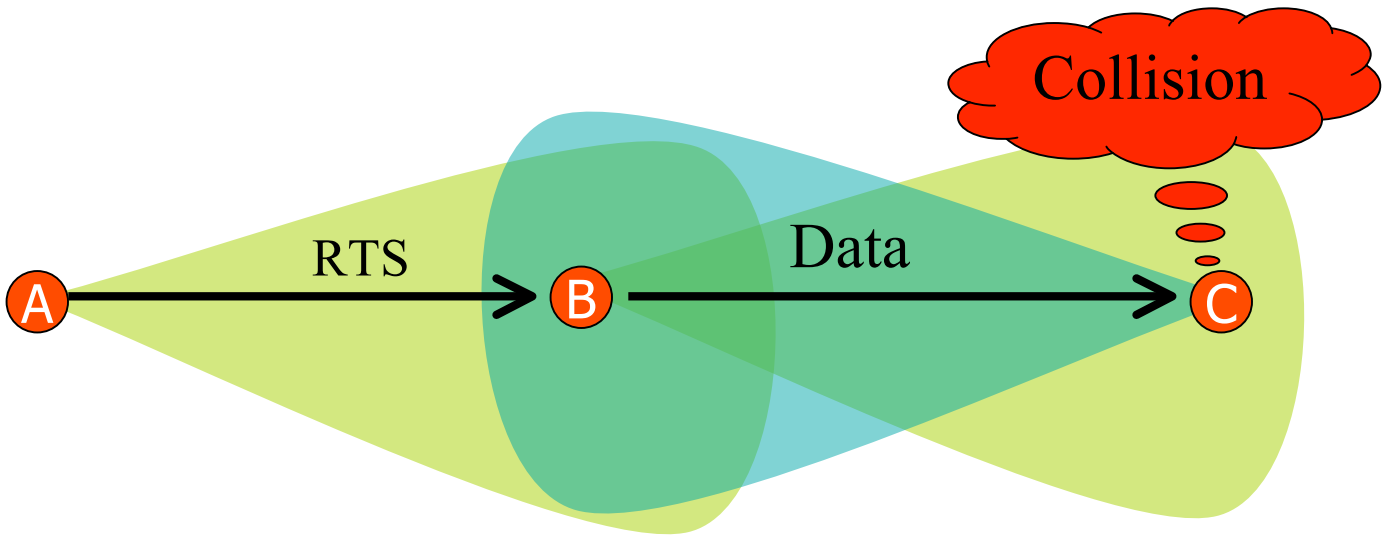
- Due to gain asymmetry



- Node A later intends to transmit to node B
  - A cannot carrier-sense B's transmission to C

New Hidden Terminal Problem

- Due to gain asymmetry



- Node A may initiate RTS meant for B
  - A can interfere at C causing collision

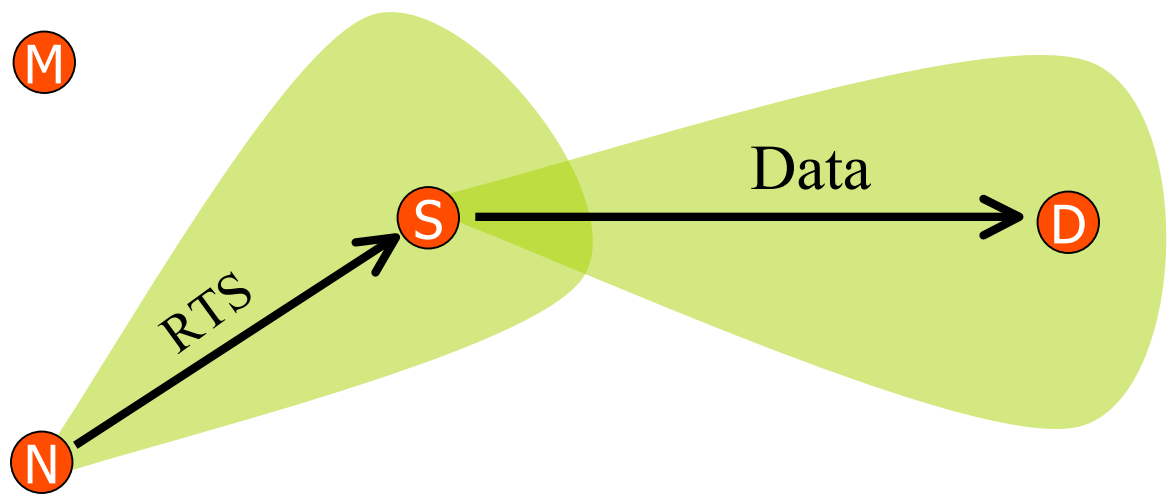
New Challenges III …

Deafness

with Directional MAC

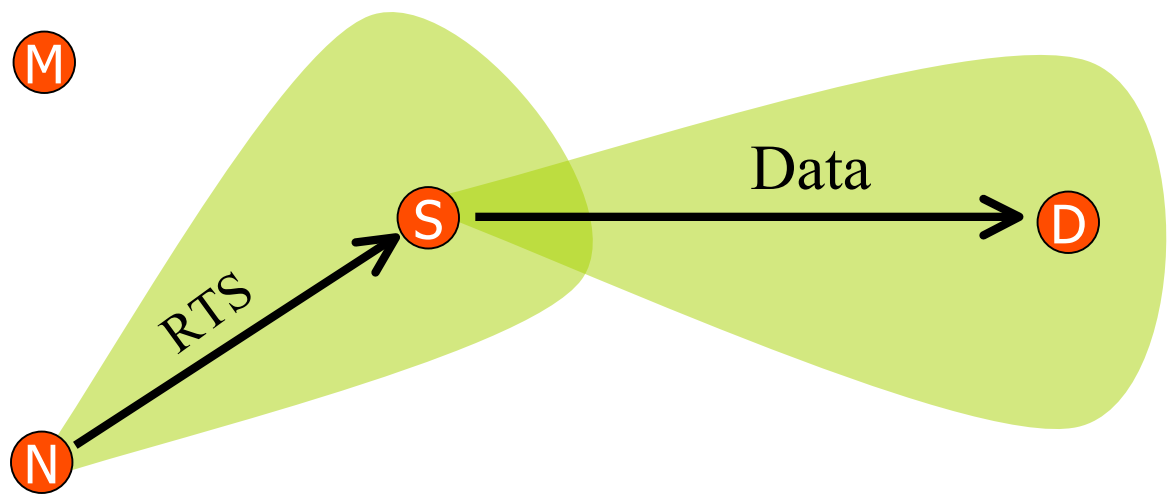
Deafness [ICNP 04]

- Node N initiates communication to S
  - S does not respond as S is beamformed toward D
  - N cannot classify cause of failure
  - Can be collision or deafness



Channel Underutilized

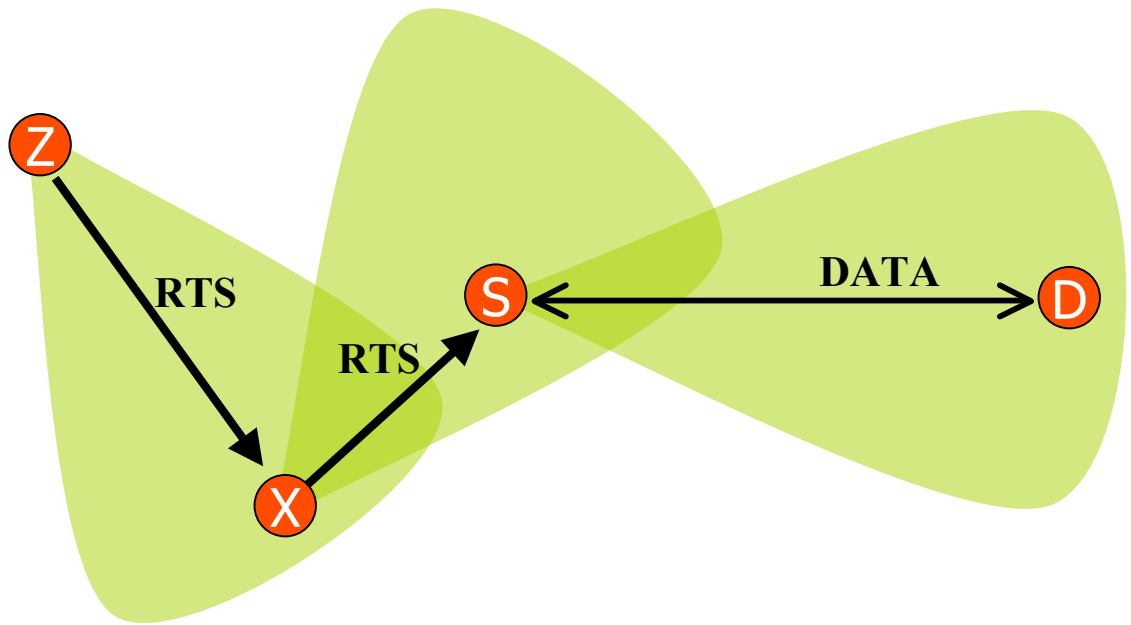
- Collision: N must attempt less often
- Deafness: N should attempt more often
  - Misclassification incurs penalty (similar to TCP)



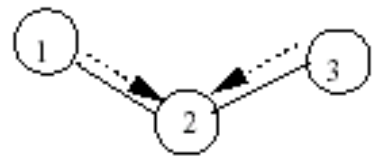
Deafness not a problem with omnidirectional antennas

Deafness and "Deadlock"

- Directional sensing and backoff ...
  - Causes S to always stay beamformed to D
  - X keeps retransmitting to S without success
  - Similarly Z to X → a "deadlock"



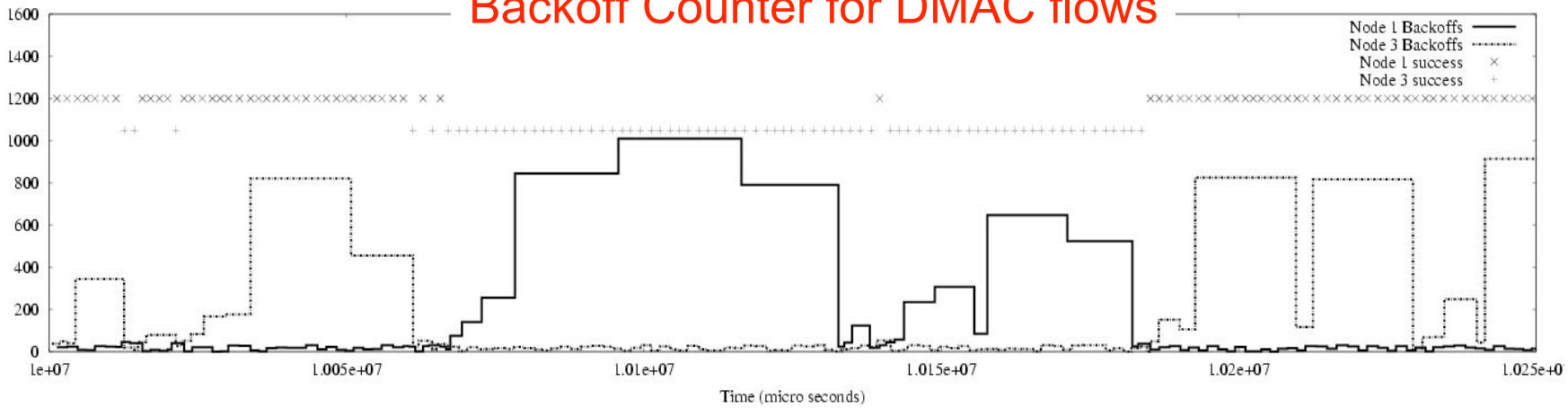
ToneDMAC's Impact



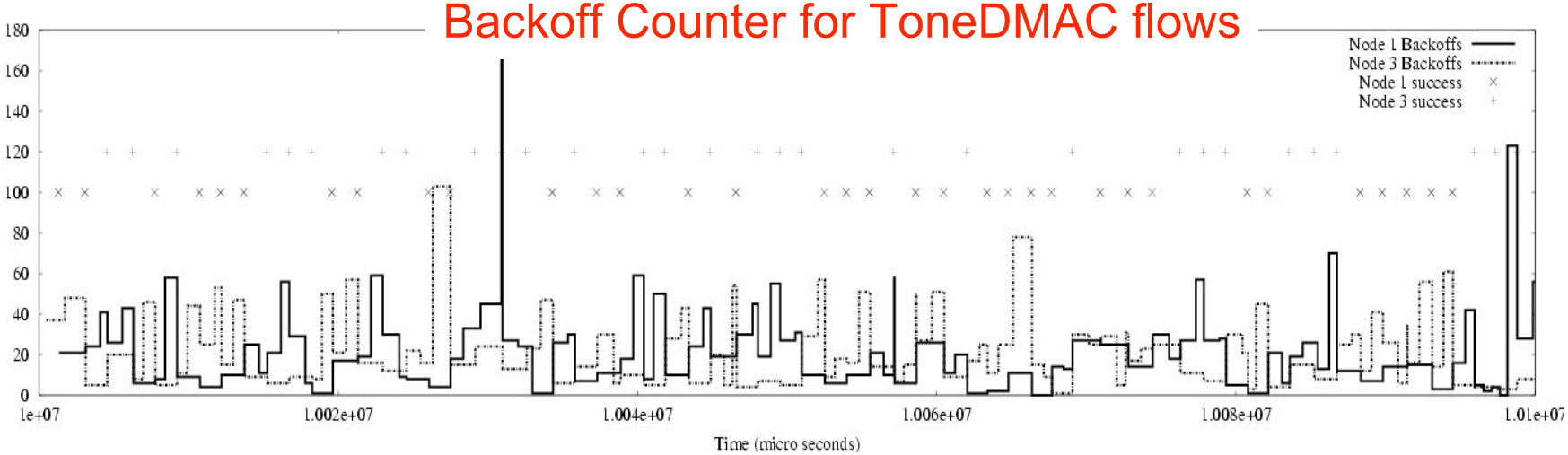
Scenario (ii)

Backoff Values

Backoff Counter for DMAC flows



Backoff Counter for ToneDMAC flows



time

New Challenges IV …

MAC-Layer Capture

The bottleneck to spatial reuse

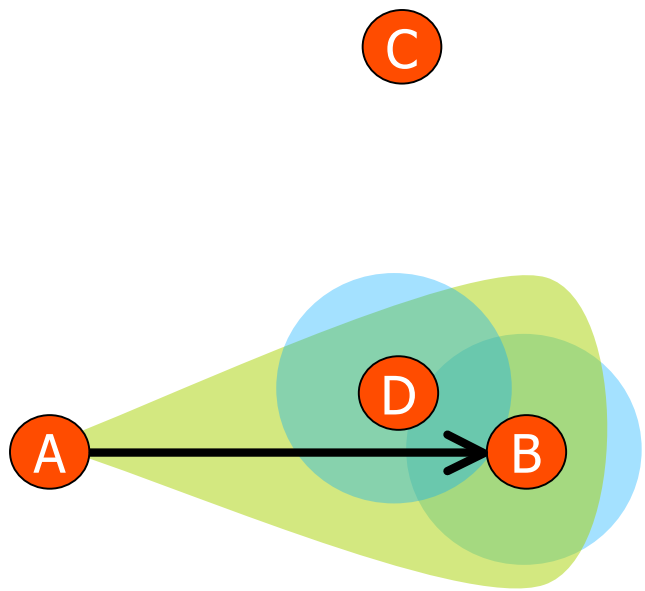
Capture [SECON 07]

- Typically, idle nodes remain in omni mode
  - When signal arrives, nodes get engaged in receiving the packet
  - Received packet passed to MAC
  - If packet not meant for that node, it is dropped

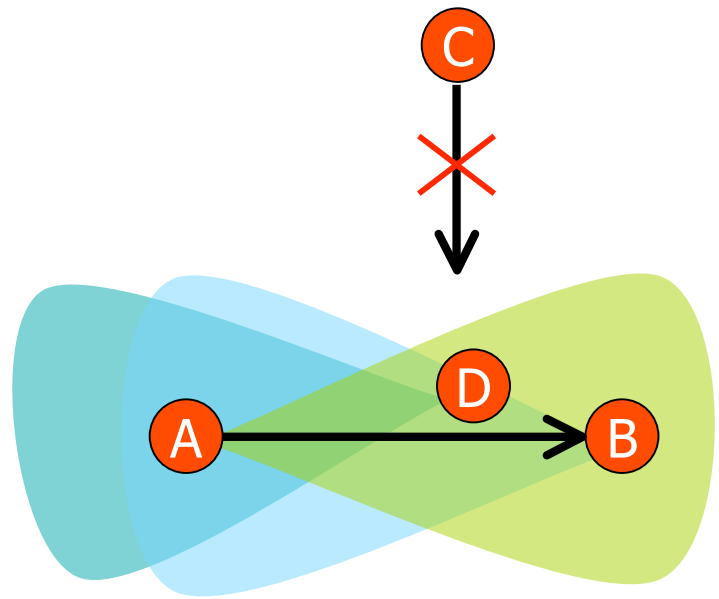
↓

Wastage because the receiver
could accomplish useful communication
instead of receiving the unproductive packet

Capture Example



Both B and D are omni when signal arrives from A



B and D beamform to receive arriving signal

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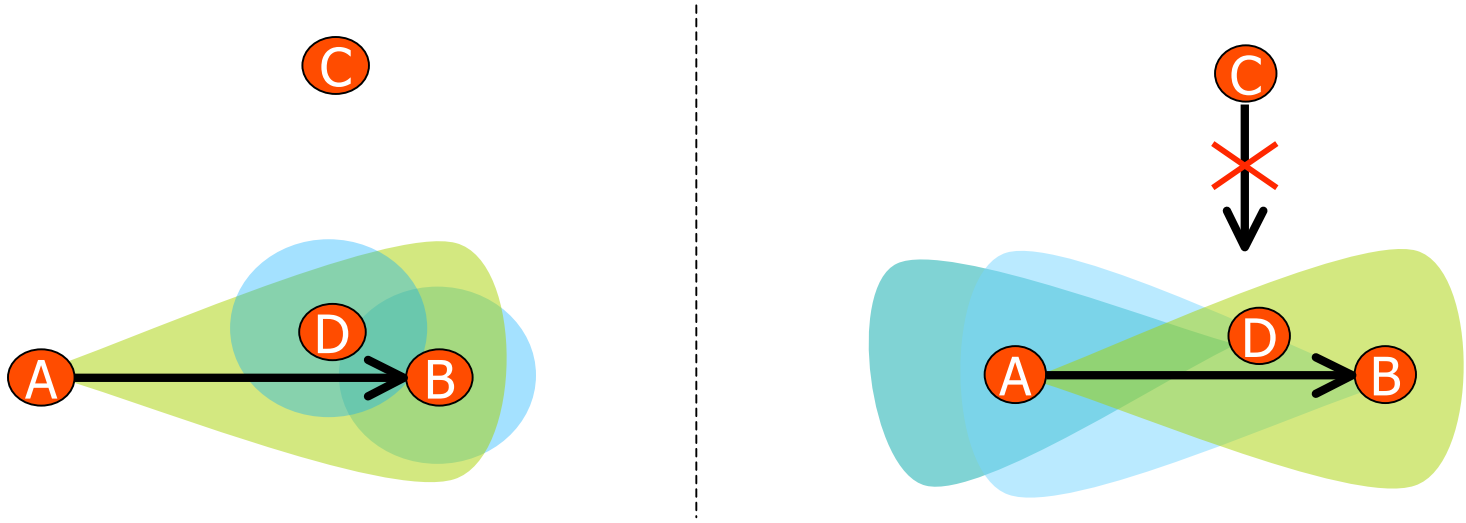
Impact of Capture

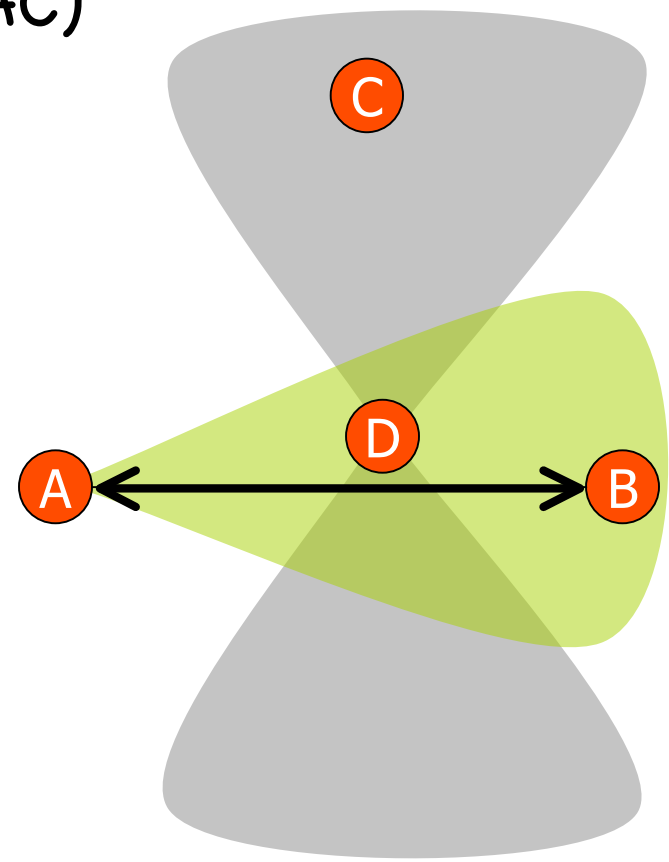


Beamforming for transmission and reception only is not sufficient

Antenna control necessary during idle state also

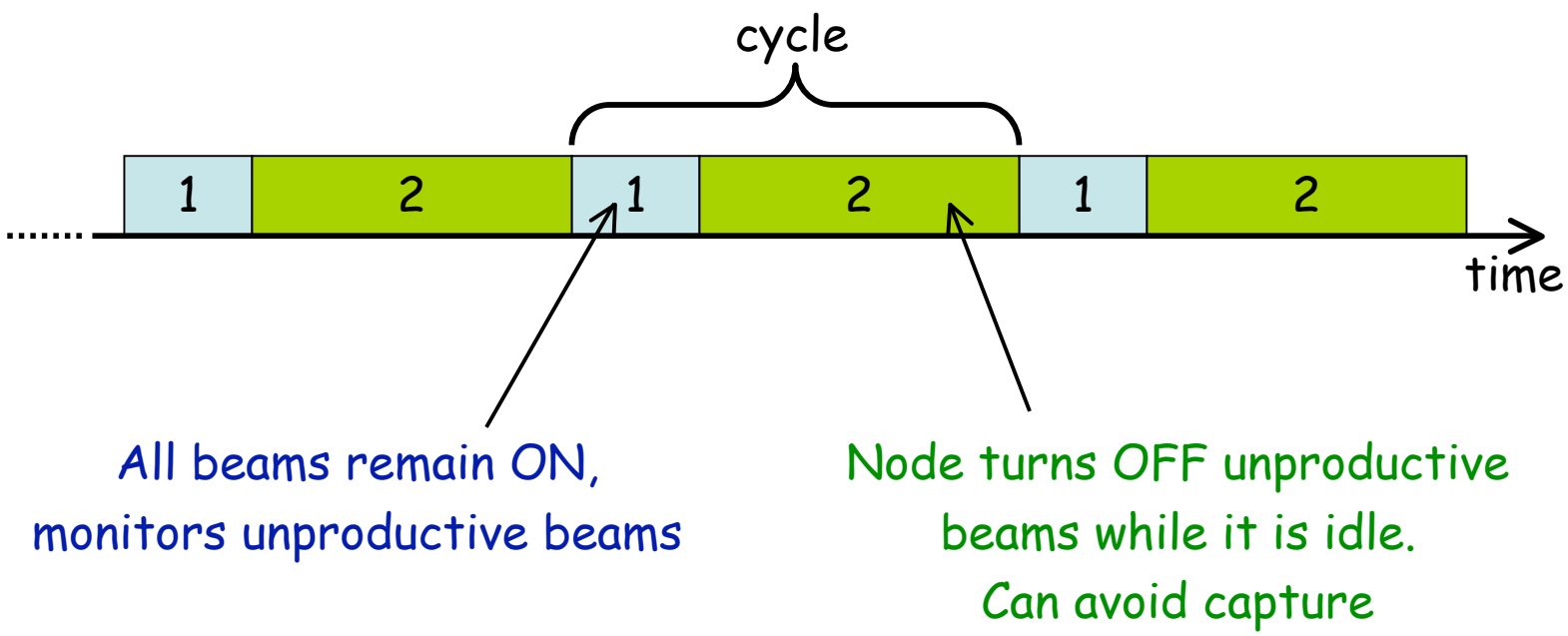
MAC Layer Solution

- Capture-Aware MAC (CaDMAC)
  - D monitors all incident traffic
  - Identifies unproductive traffic
  - Beams that receive only unproductive packets are turned off
  - However, turning beams off can prevent useful communication in future



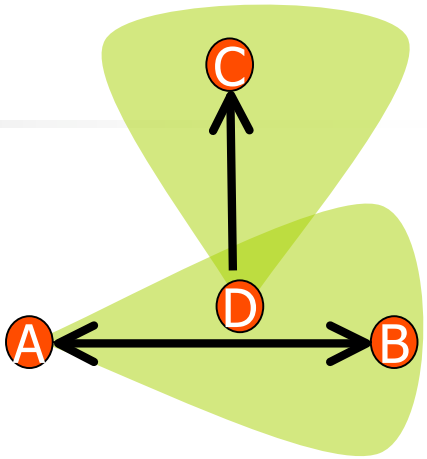
CaDMAC Time Cycles

- CaDMAC turns off beams periodically
  - Time divided into cycles
  - Each cycle consists of
    1. Monitoring window + 2. Filtering window

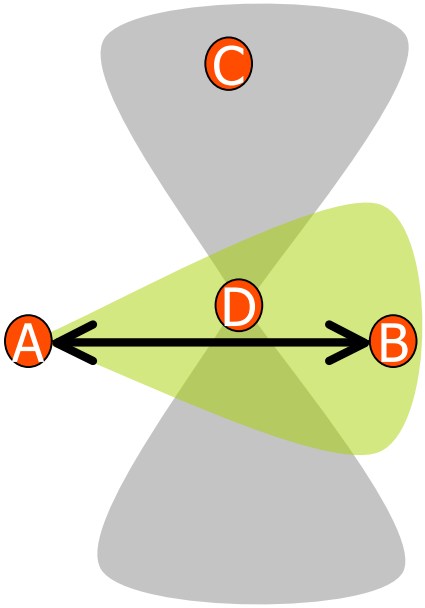


CaDMAC Communication

- Transmission / Reception uses only necessary single beam

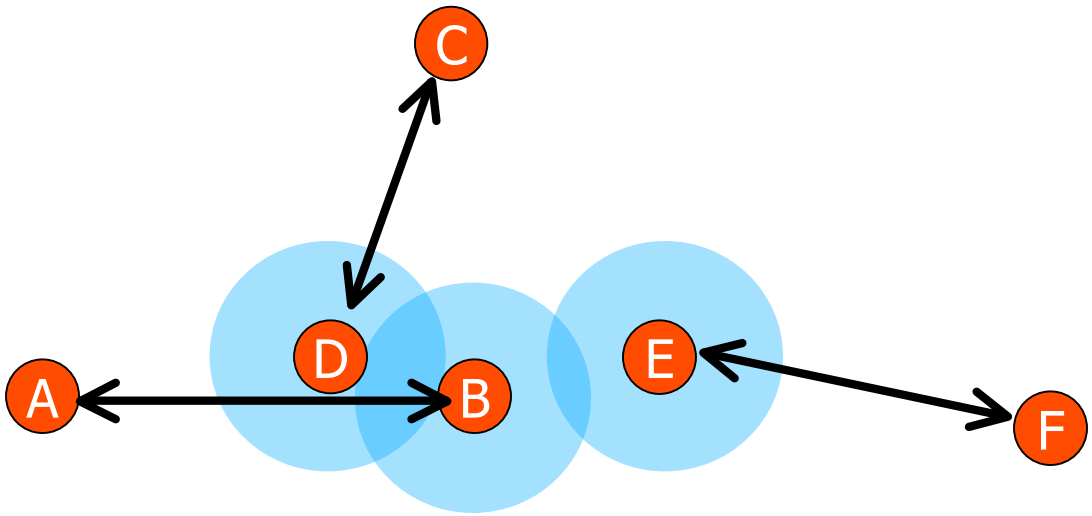


- When node becomes idle, it switches back to appropriate beam pattern
  - Depending upon current time window



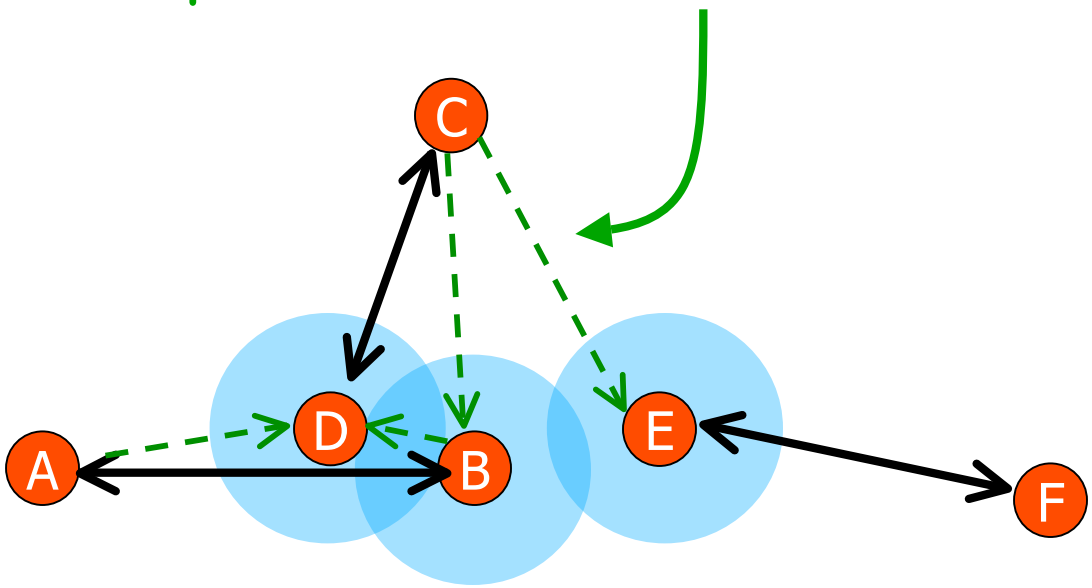
Spatial Reuse in CaDMAC

- During Monitoring window, idle nodes are omni



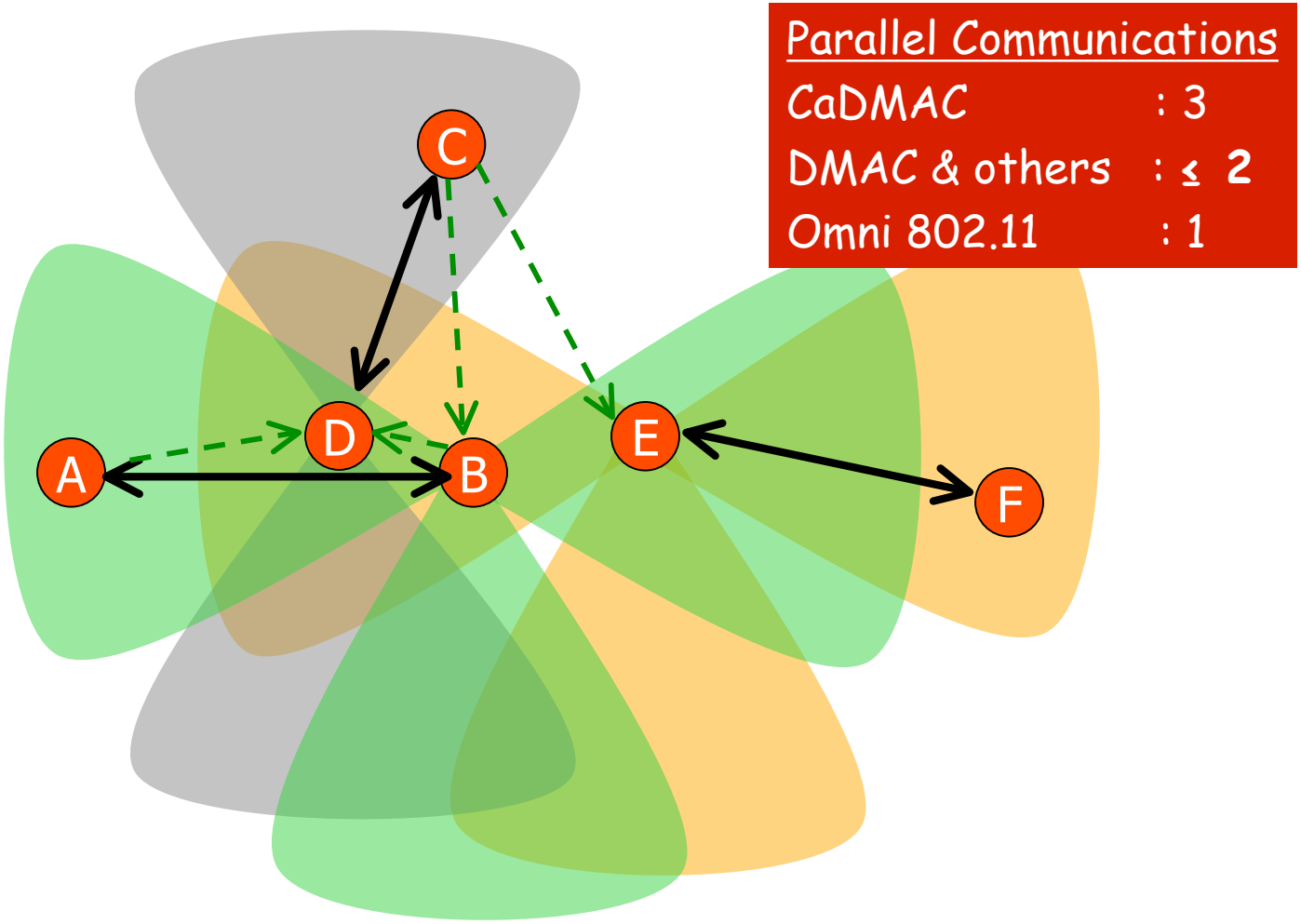
Spatial Reuse in CaDMAC

- At the end of Monitoring window CaDMAC identifies unproductive links



Spatial Reuse in CaDMAC

- During Filtering window → use spatial filtering



Network Transport Capacity

- Transport capacity defined as:

  bit-meters per second

  (like man-miles per day for airline companies)

- Capacity analysis

$$\left.\begin{aligned} &\sum_{bit=1}^{\lambda nT}\sum_{h=1}^{h(bit)} r_{bit}^{h} \geq \lambda nTL \\ &\sum_{bit=1}^{\lambda nT}\sum_{h=1}^{h(bit)} kr^{2} \leq WT.A \end{aligned}\right\} Lim_{n\to\infty} O\left(\frac{W}{\sqrt{n}}\right)$$

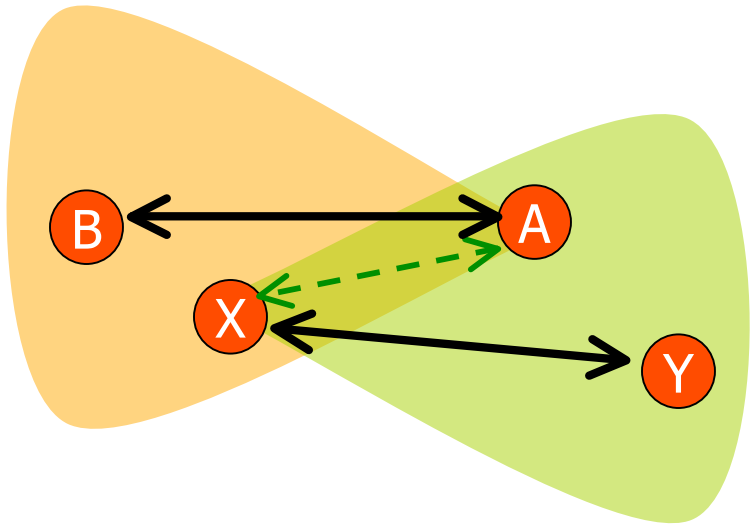
Directional Capacity

- Existing results show
  - Capacity improvement lower bounded by $O\left(\frac{2\pi}{\sqrt{\theta\beta}}\right)$
  - Results do not consider side lobes of radiation patterns
- We consider main lobe and side lobe gains (g_m and g_s)
- We find capacity upper bounded by $\left(\frac{1}{\sqrt{\pi}}\left(\frac{2}{\beta}\right)^{\frac{1}{\alpha}}\frac{W}{n^{\frac{1}{\alpha}}}\right)\left(\frac{g_m}{g_s}\right)^{\frac{2}{\alpha}}$
  - i.e., improvement of $O\left(\left(\frac{g_m}{g_s}\right)^{\frac{2}{\alpha}}\right)$

CaDMAC still below achievable capacity

Discussion

- CaDMAC cannot eliminate capture completely



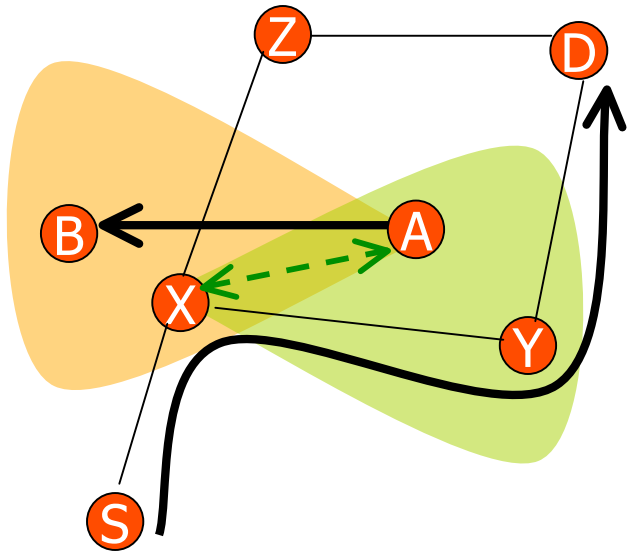
  - Happens because CaDMAC cannot choose routes
  - Avoiding capture-prone links → A routing problem

Routing using Beamforming Antennas

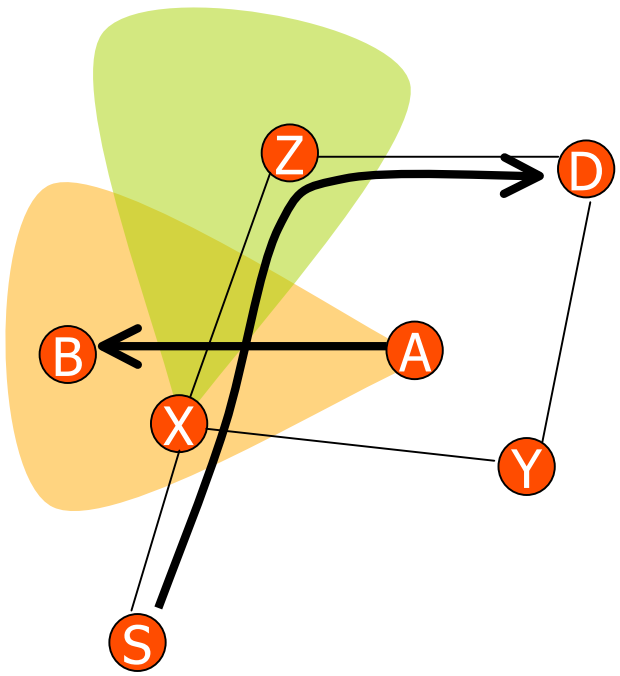
Incorporating capture-awareness

Motivating Capture-Aware Routing

- Find a route from S to D, given A→B exists
  - Options are SXYD, SXZG



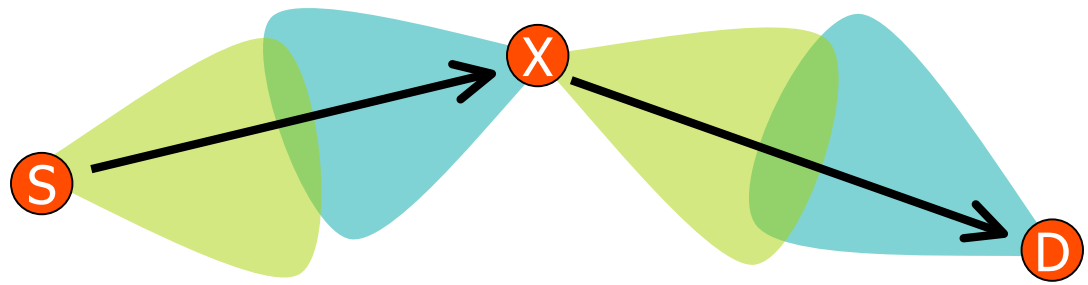
Capture



No Capture

Measuring Route Cost

- Sum capture costs of all beams on the route
  - Capture cost of a Beam *j* =
    how much unproductive traffic incident on Beam *j*



- Route's hop count
- Cost of participation
  - How many intermediate nodes participate in cross traffic

Unified Routing Metric

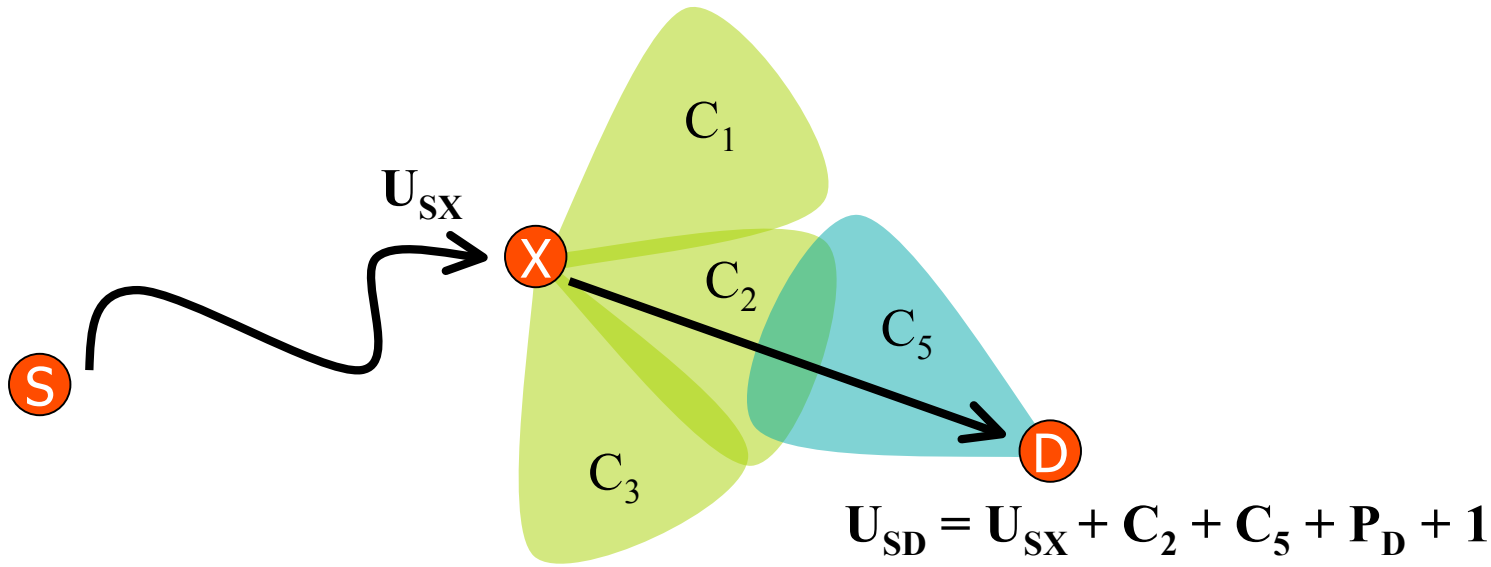
- U_{route} = Weighted Combination of
  1. Capture cost (K)
  2. Participation cost (P)
  3. Hop count (H)

$$U_{route} = \sum_{ij \in route} \omega_k \kappa_{ij} + \omega_p P_i + H_{ij}$$

- Weights chosen based on sensitivity analysis

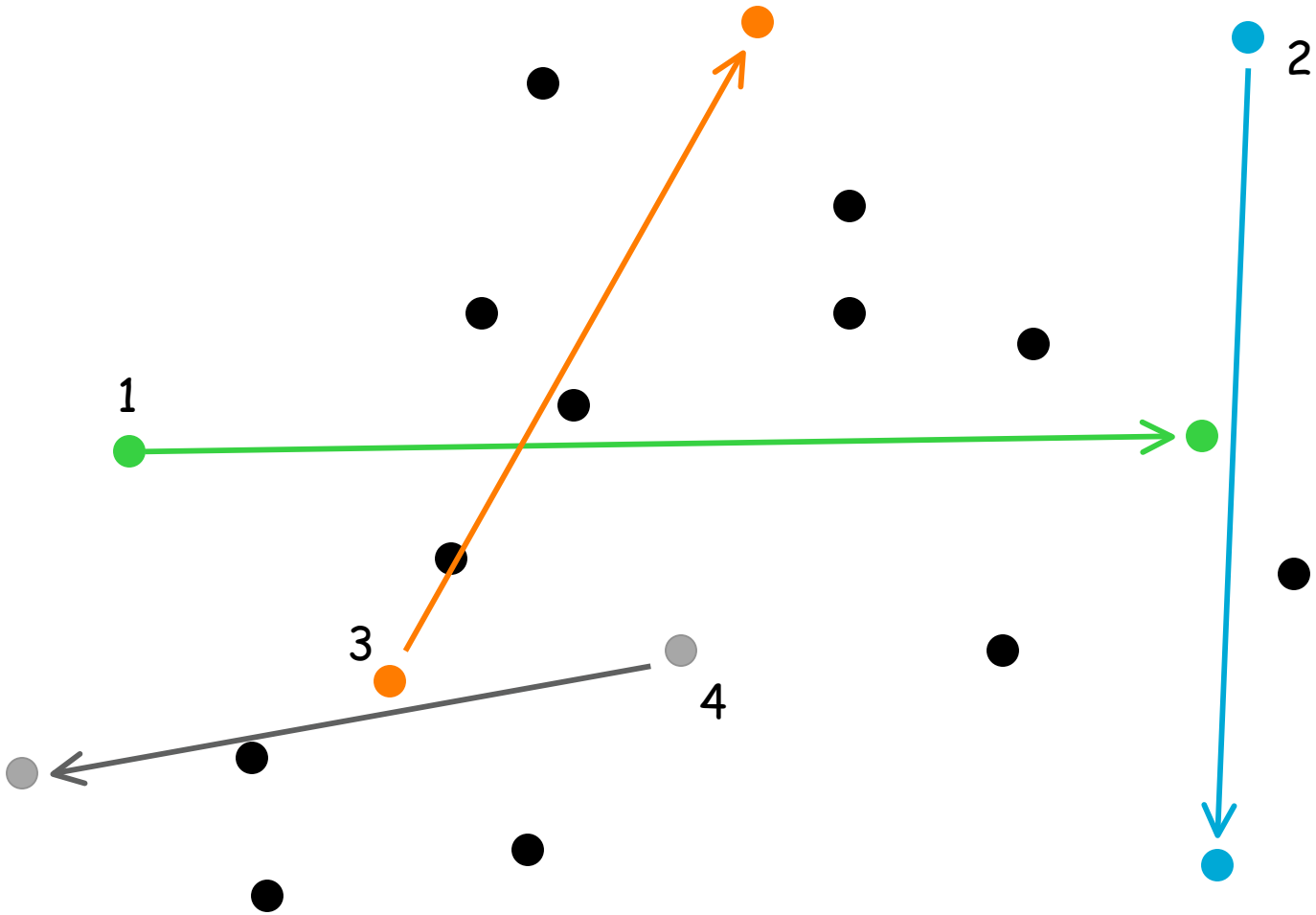
Protocol Design

- Source routing protocol (like DSR)
  - Intermediate node X updates route cost from S - X

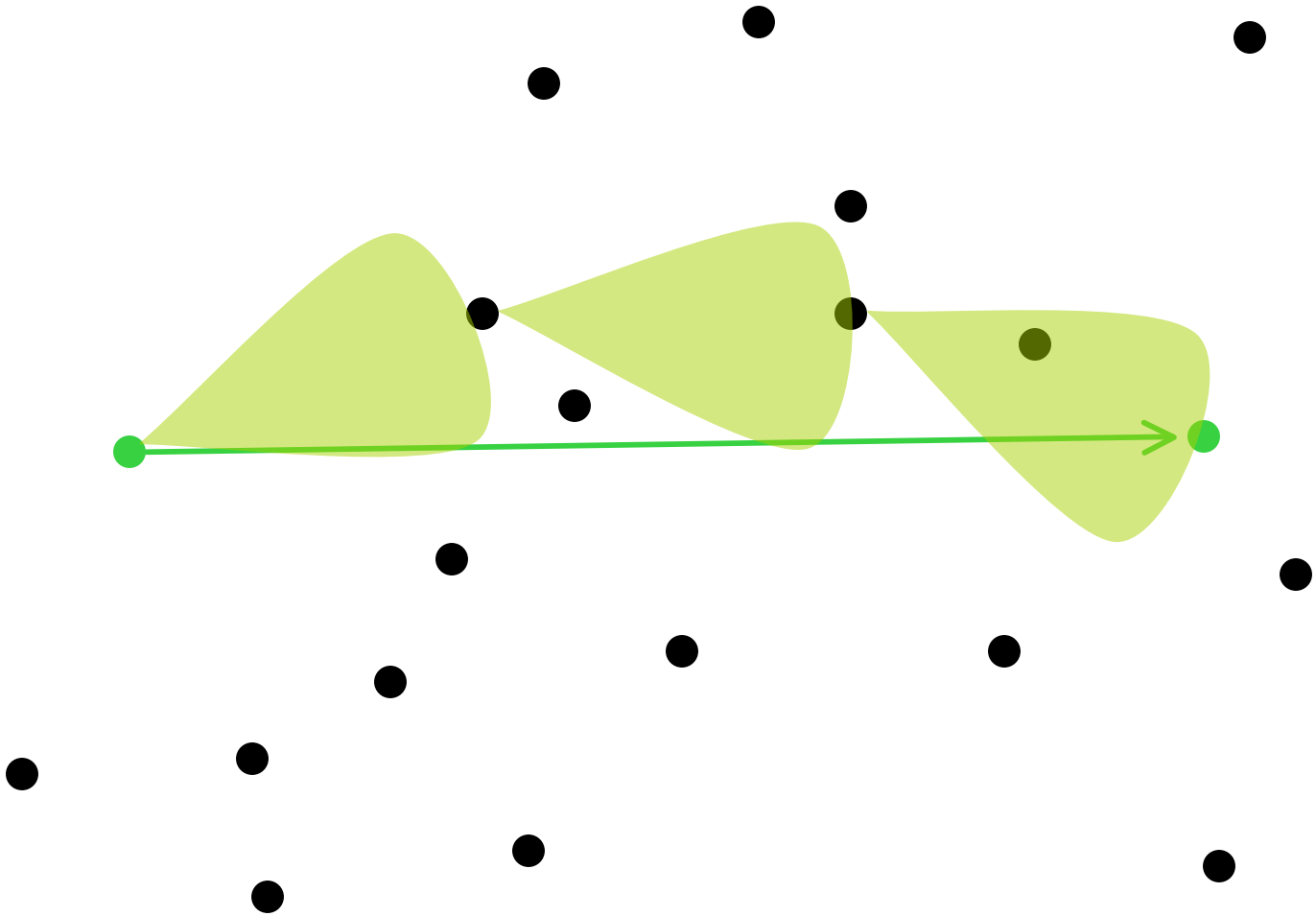


  - Destination chooses route with least cost (U_{route})
  - Routing protocol shown to be loop-free

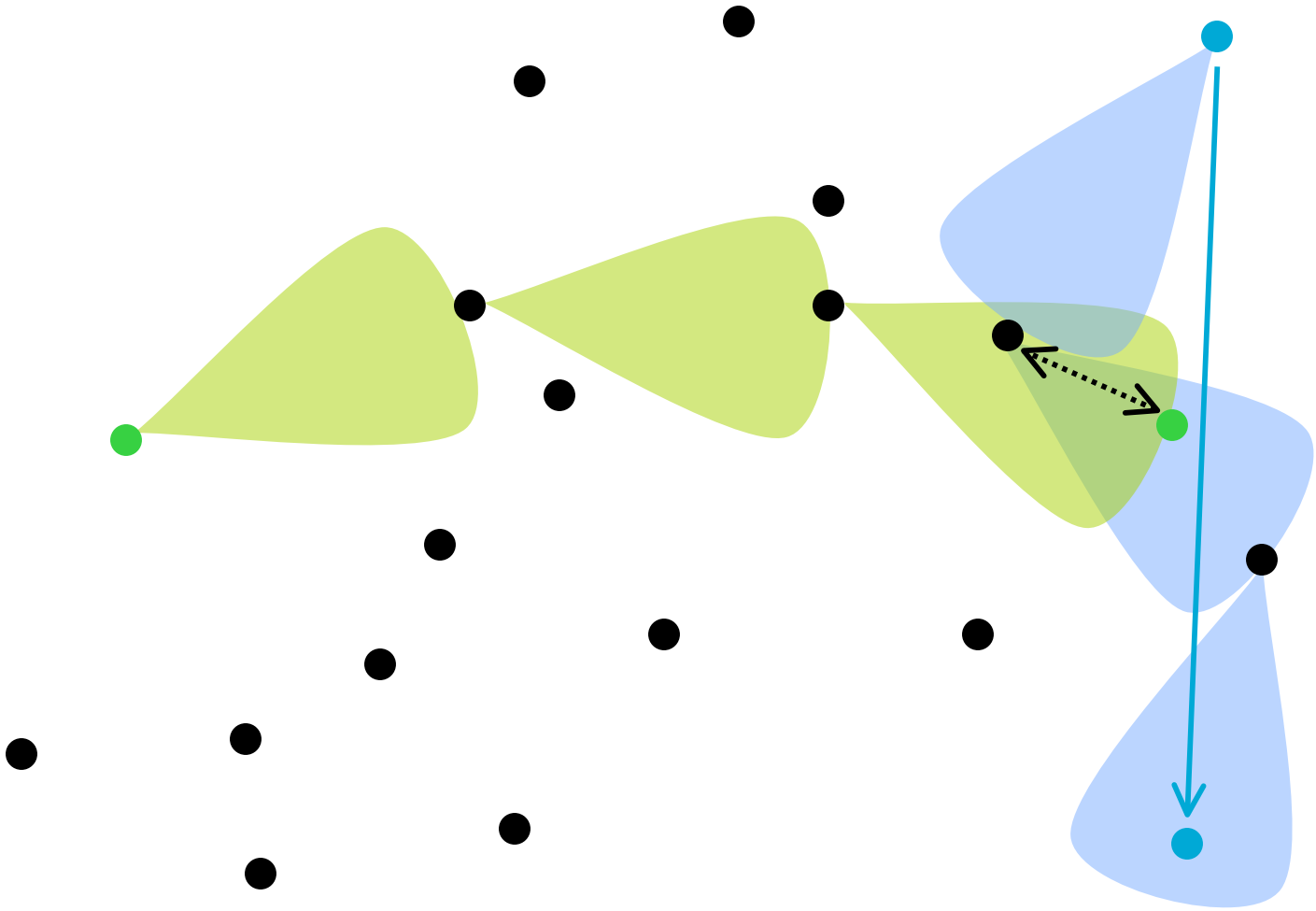
CaRP Vs DSR



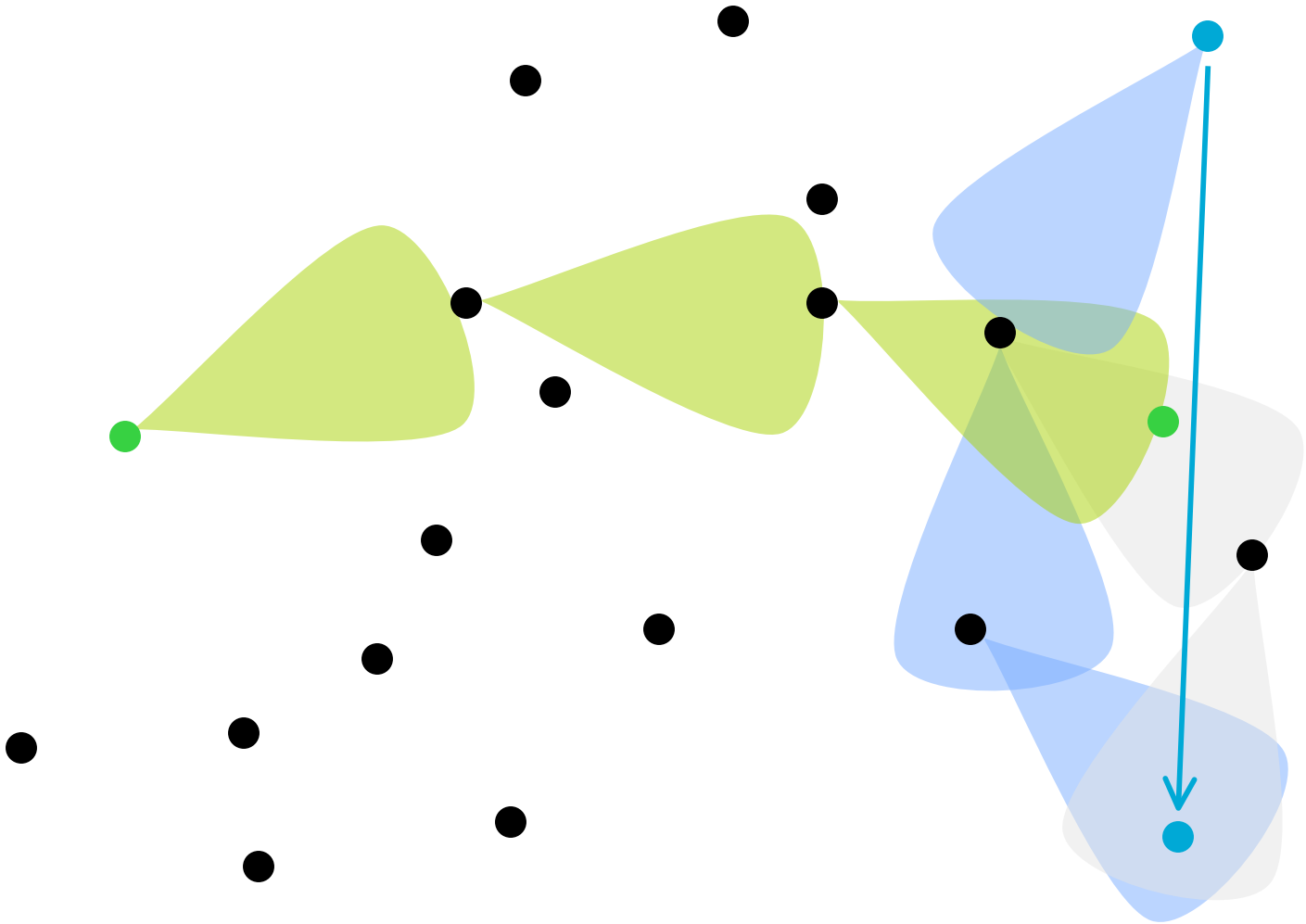
CaRP Vs DSR



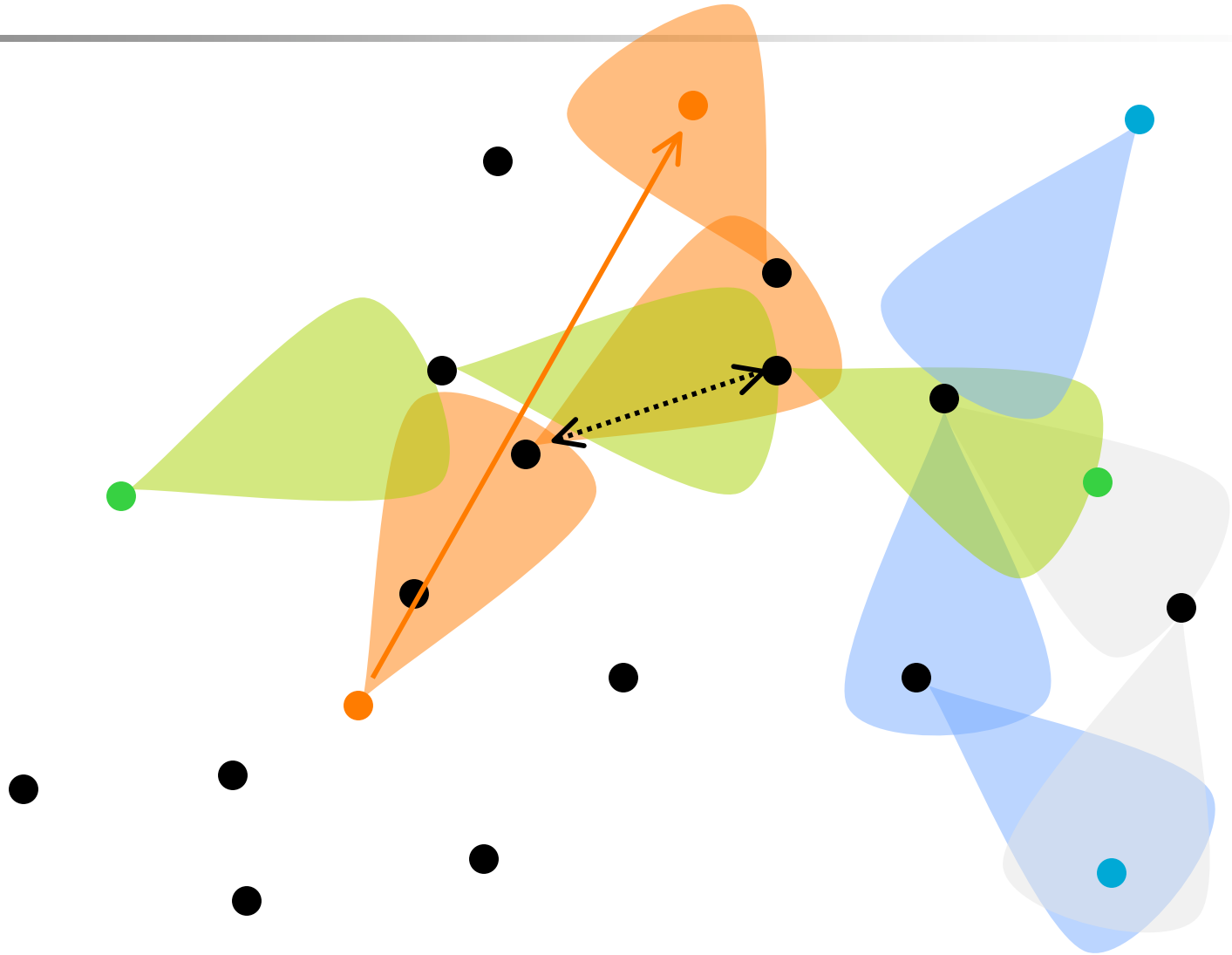
CaRP Vs DSR



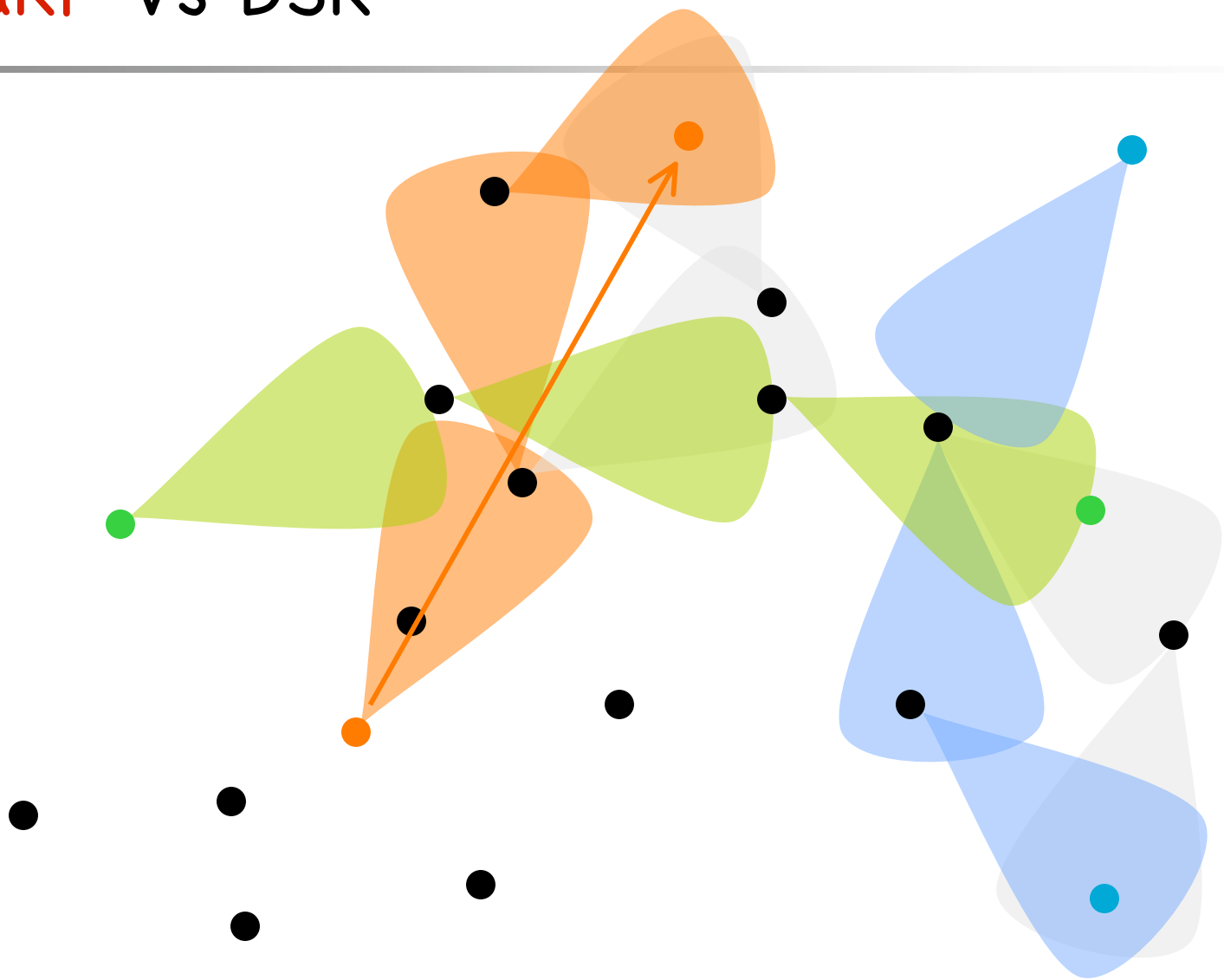
CaRP Vs DSR



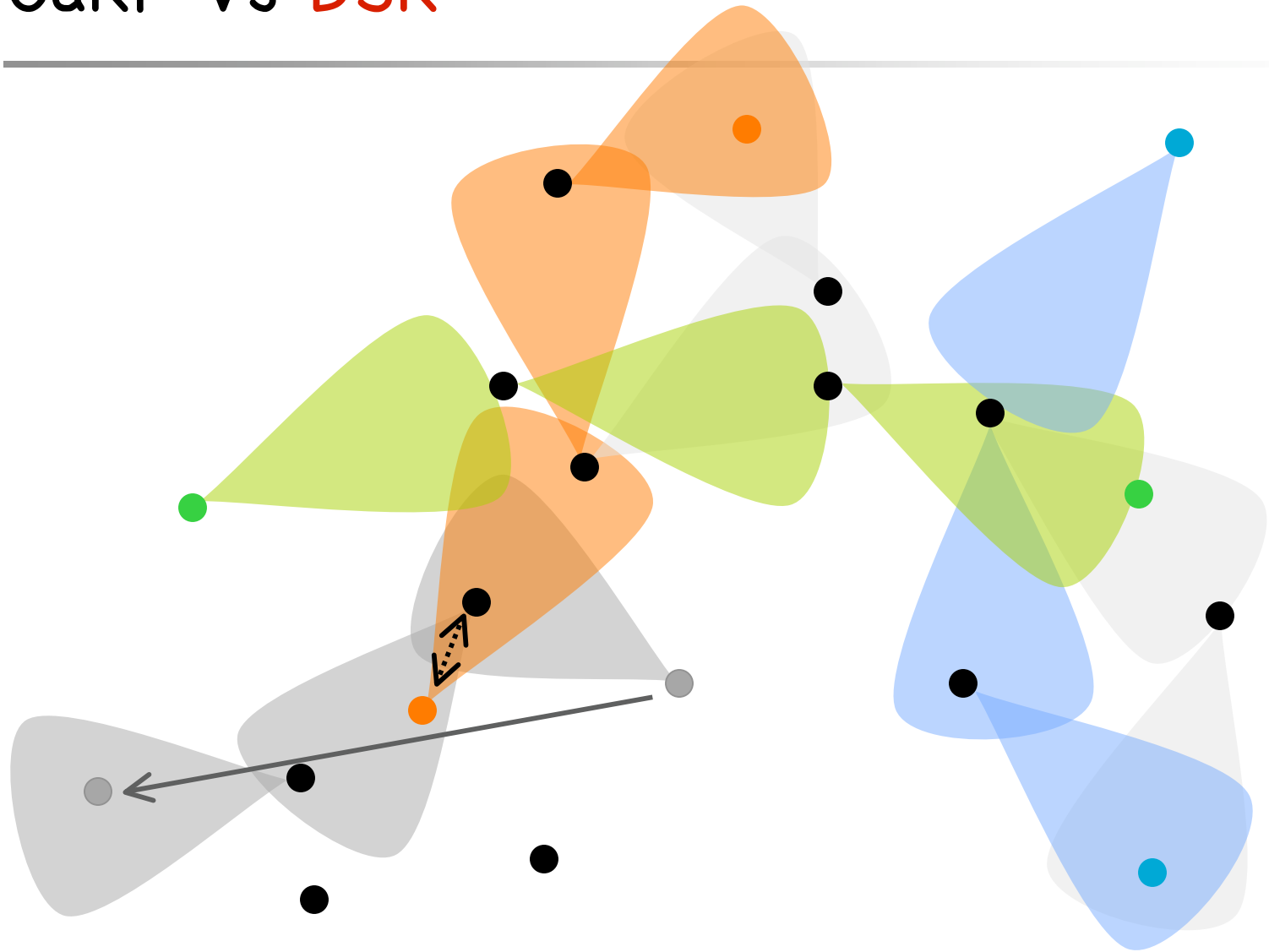
CaRP Vs DSR



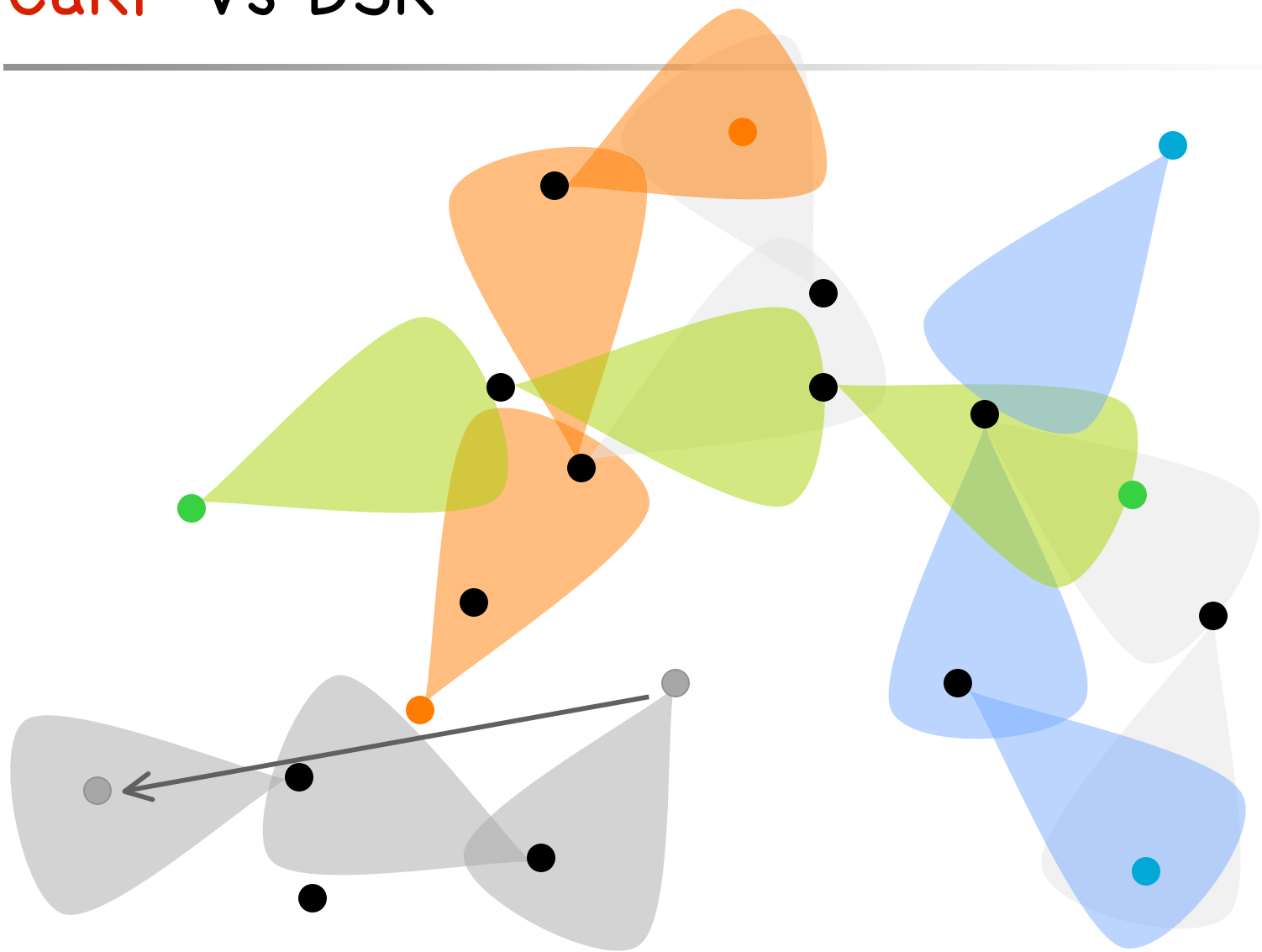
CaRP Vs DSR



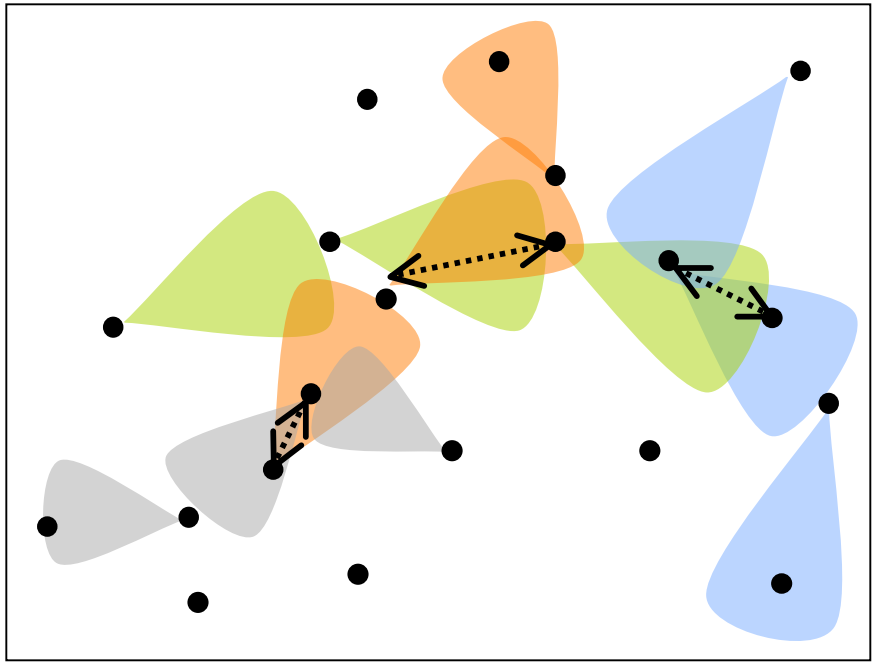
CaRP Vs DSR



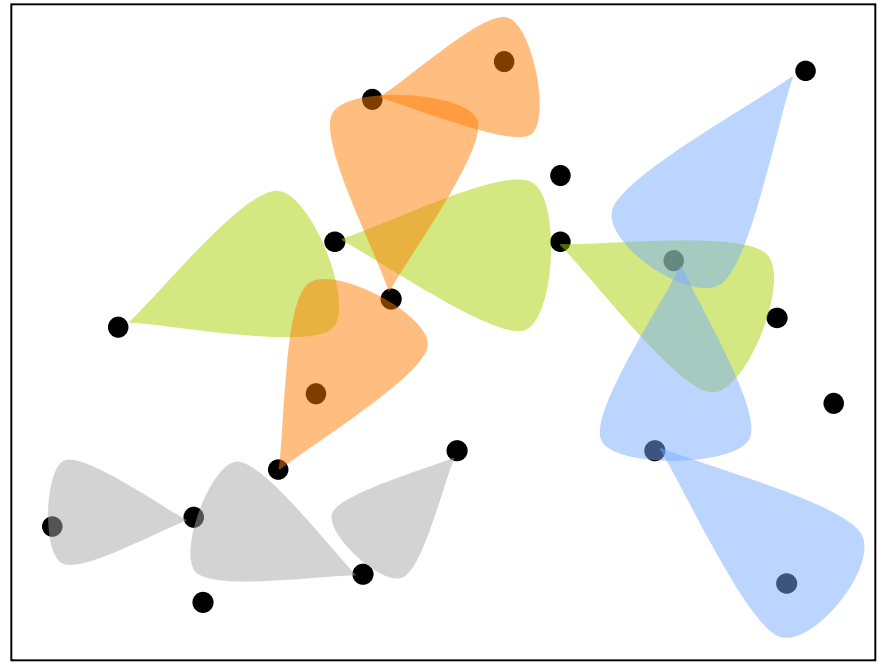
CaRP Vs DSR



CaRP Vs DSR



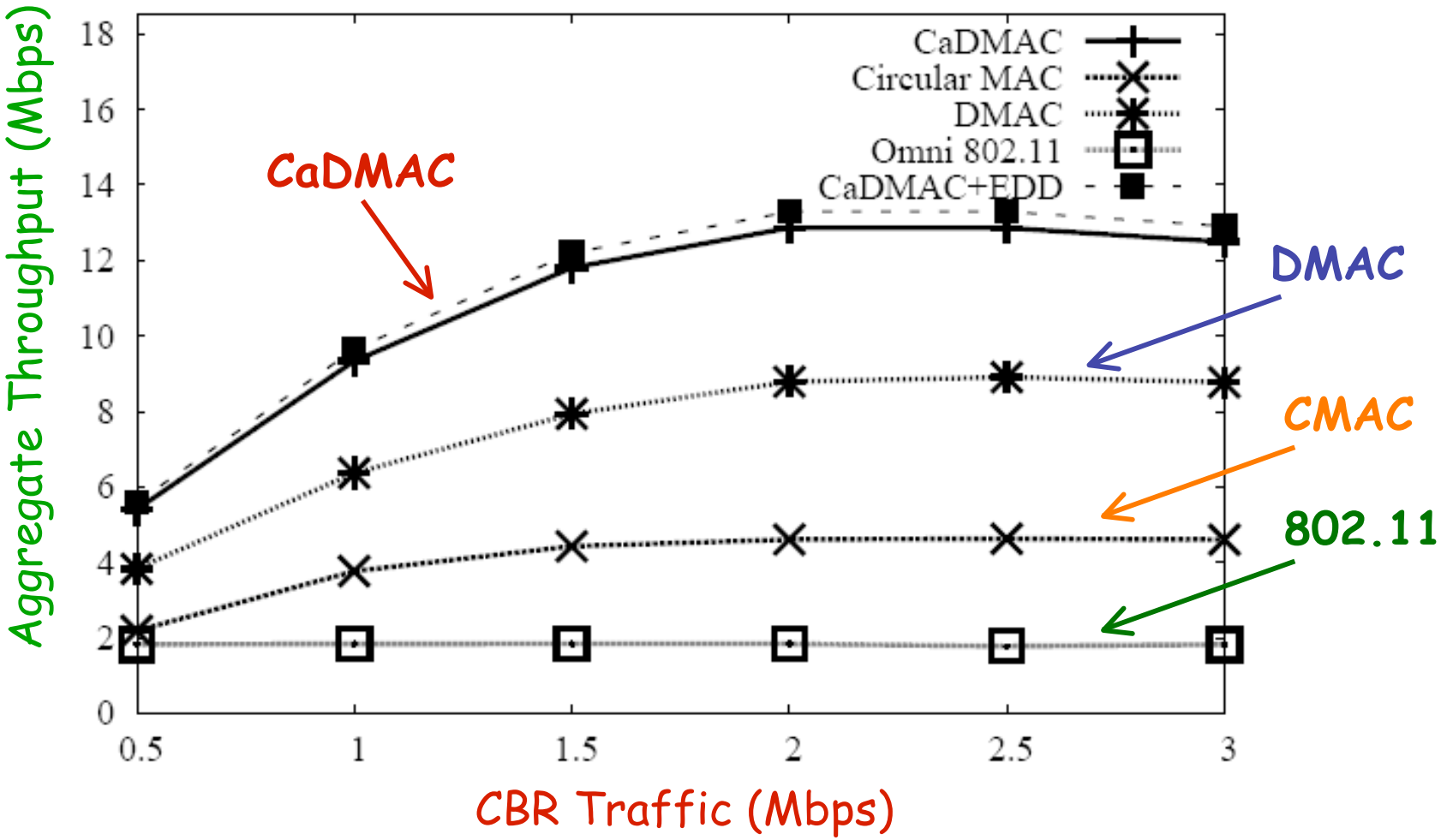
DSR



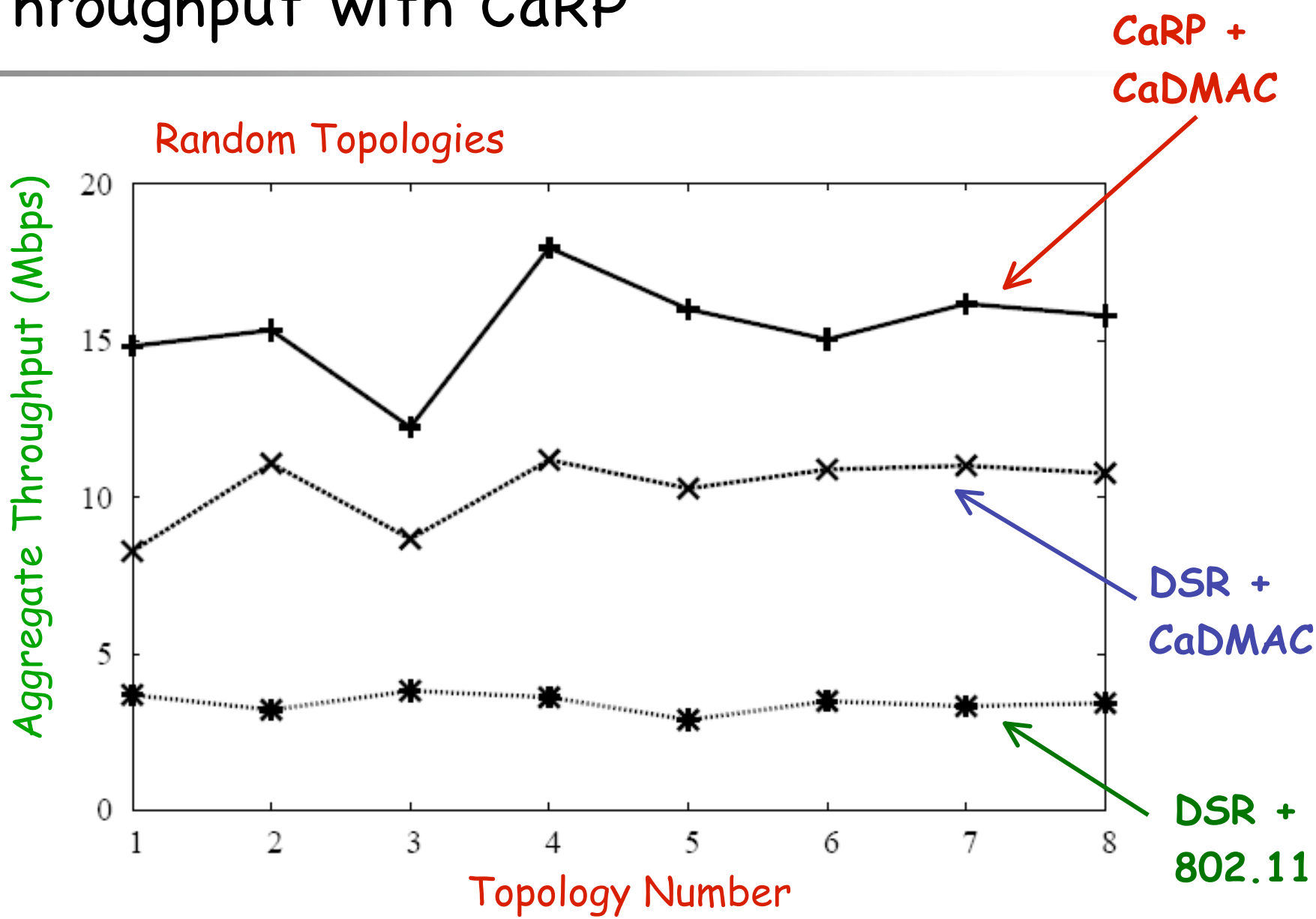
CaRP

CaRP prefers a traffic-free direction
"Squeezes in" more traffic in given area

Performance of CaDMAC



Throughput with CaRP



Outline / Contribution

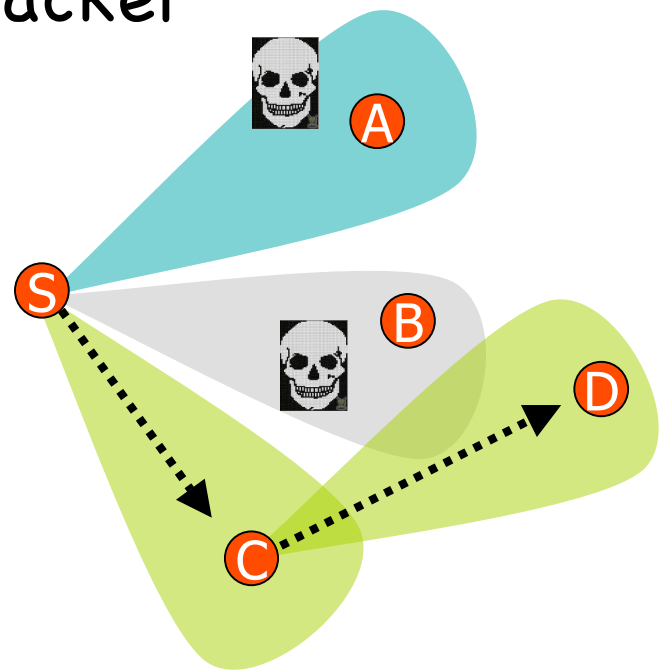
- Antenna Systems → A closer look
- New challenges with beamforming antennas
- Design of MAC and Routing protocols
  - MMAC, ToneDMAC, CaDMAC
  - DDSR, CaRP
  - Cross-Layer protocols – Anycasting
  - Improved understanding of theoretical capacity
  - Security
- Experiment with prototype testbed

Security and Privacy

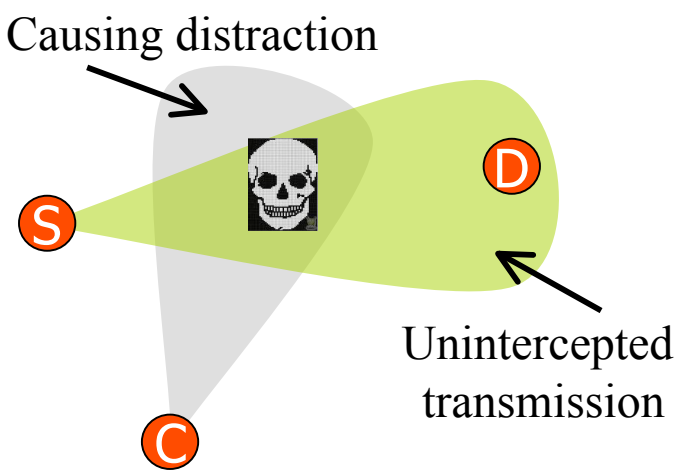
- Growing concern in security and privacy
  - Can make/break wireless systems
- Many wireless attacks
  - Leverage the feasibility of easy overhearing
  - Facilitated by omnidirectional communication
- New opportunities with beamforming
  - Guide toward trusted receiver
  - Steer away from untrusted parties
  - Use diversity to detect malicious behavior

Attacker Bypassing

- Feasible to ``skirt'' around attacker
  - Disallow from overhearing all
    - MAC-Layer Anycasting
  - Route repair for bypassing



- Cause attacker distraction



Verification through Diversity

- Spatial diversity useful for verification
  - Example in Sybil Attack
    - Attacker pretends to be multiple entities
- Privacy preserving verification possible
  - All locations of nodes are requested
  - Beamformed in random sequence
    - In each transmission, random number transmitted
  - Finally, all nodes requested to report all numbers
  - Sybil attacker cannot be at all locations
    - Will be caught

Outline / Contribution

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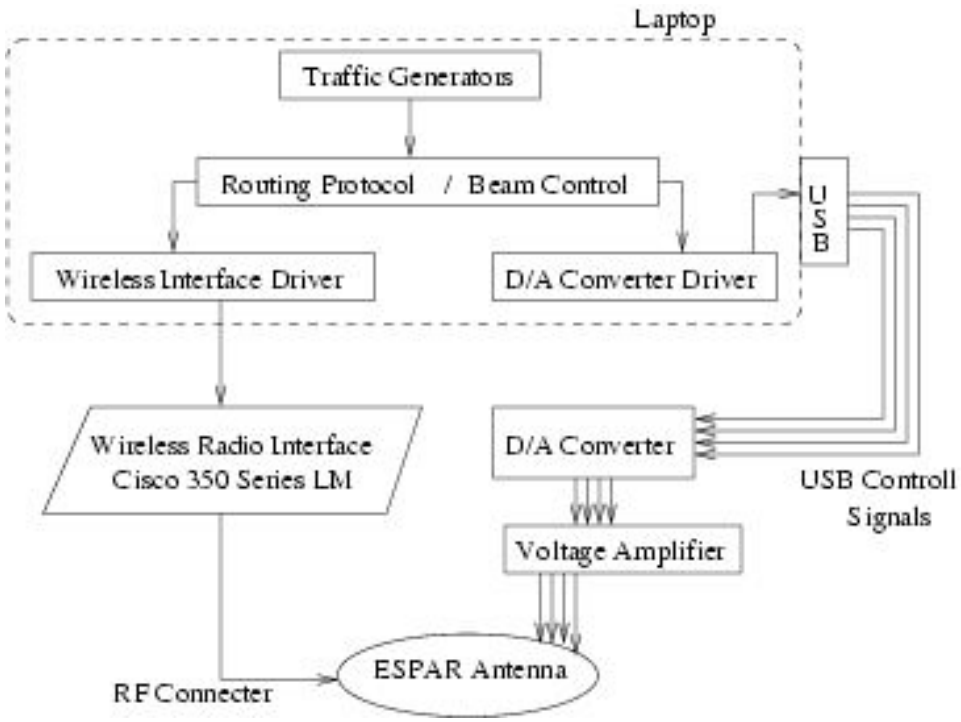
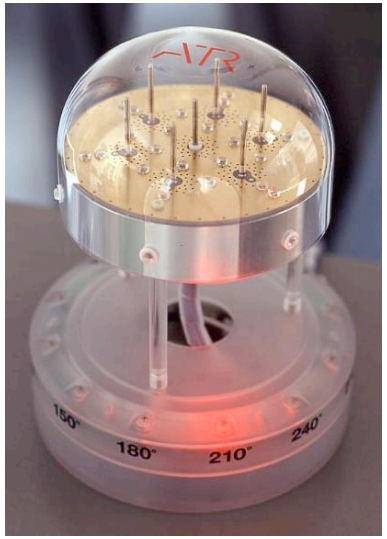
  - DDSR, CaRP
  - Cross-Layer protocols – Anycasting
  - Improved understanding of theoretical capacity
  - Security
- Experiment with prototype testbed

Testbed Prototype [VTC 05, Mobihoc 05 Poster]

- Network of 6 laptops using ESPAR antennas
  - ESPAR attached to external antenna port
  - Beams controlled from higher layer via USB

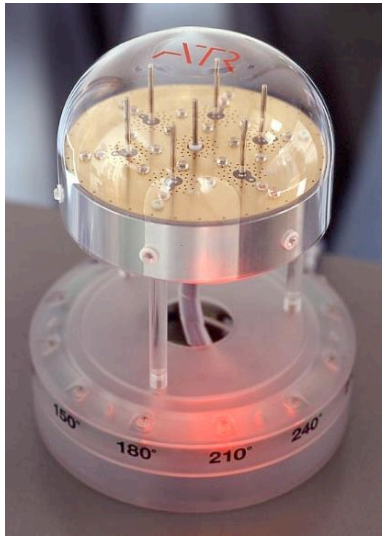




Testbed Prototype

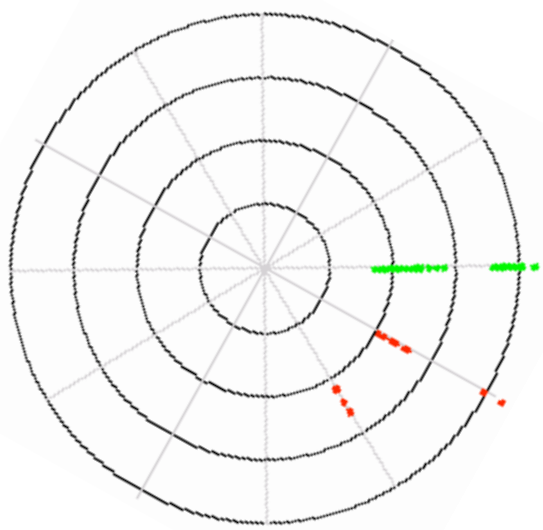
- Network of 6 laptops using ESPAR antennas
  - ESPAR attached to external antenna port
  - Beams controlled from higher layer via USB

- Validated basic operations and tradeoffs
  - Neighbor discovery
    - Observed multipath
    - 60 degrees beamwidth useful
  - Basic link state routing
    - Improves route stability
    - Higher throughput, less delay

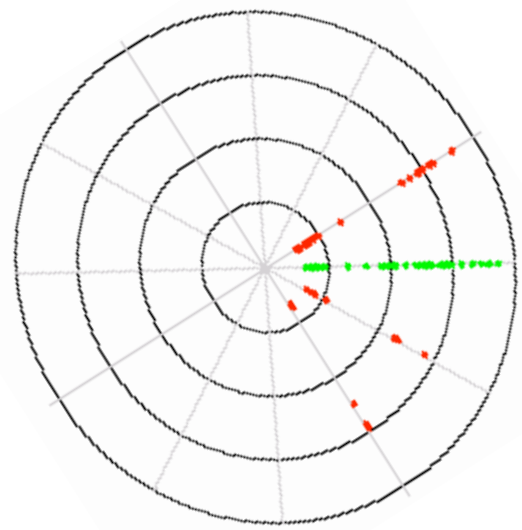


Neighbor Discovery

- Non LOS and multipath important factors
- However, 60 degree beamwidth useful



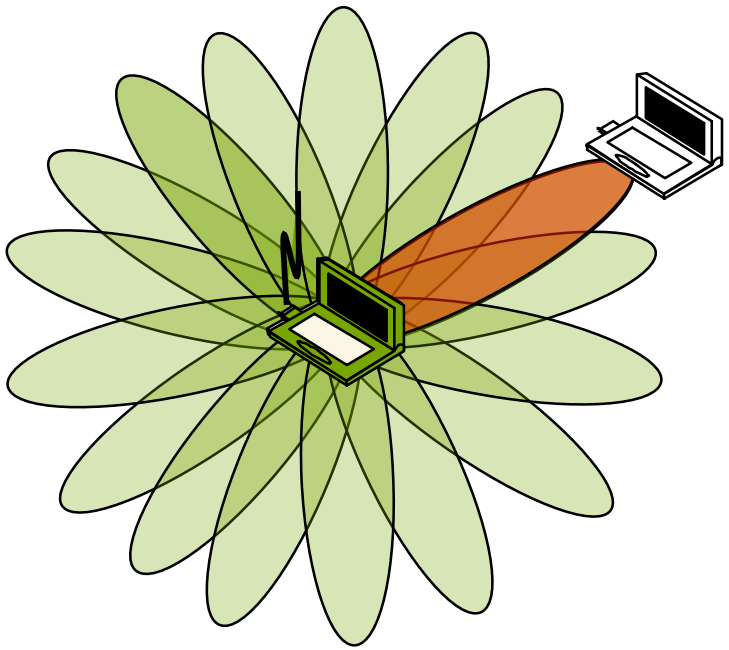
Anechoic Chamber

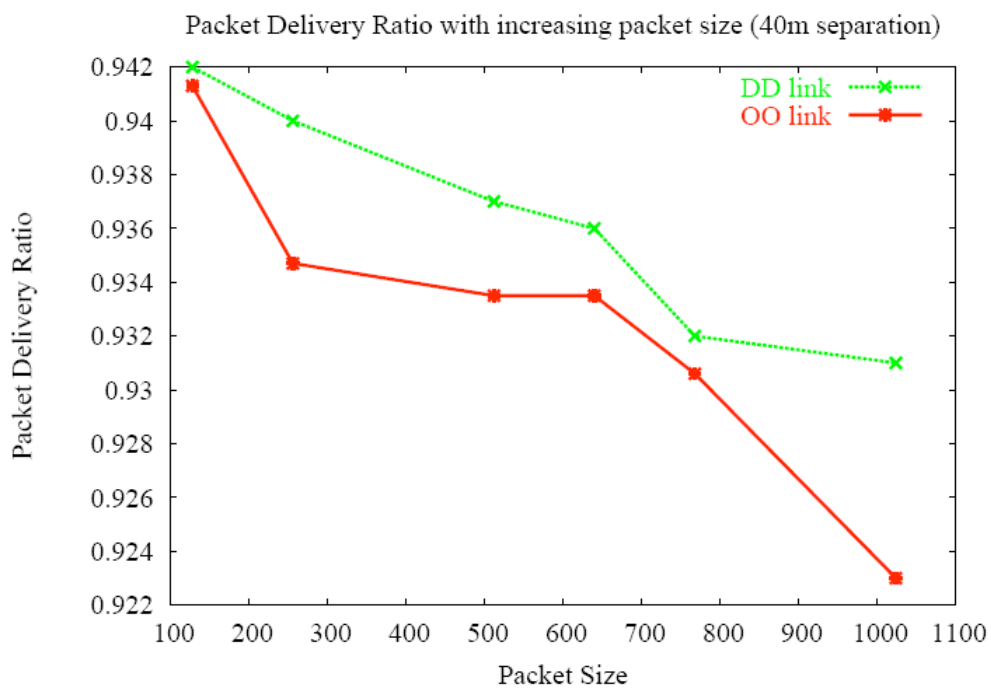


Office Corridor

Route Reliability

- Routes discovered using sweeping – DO links
  - Data Communication using DD links
  - Improved SINR improves robustness against fading

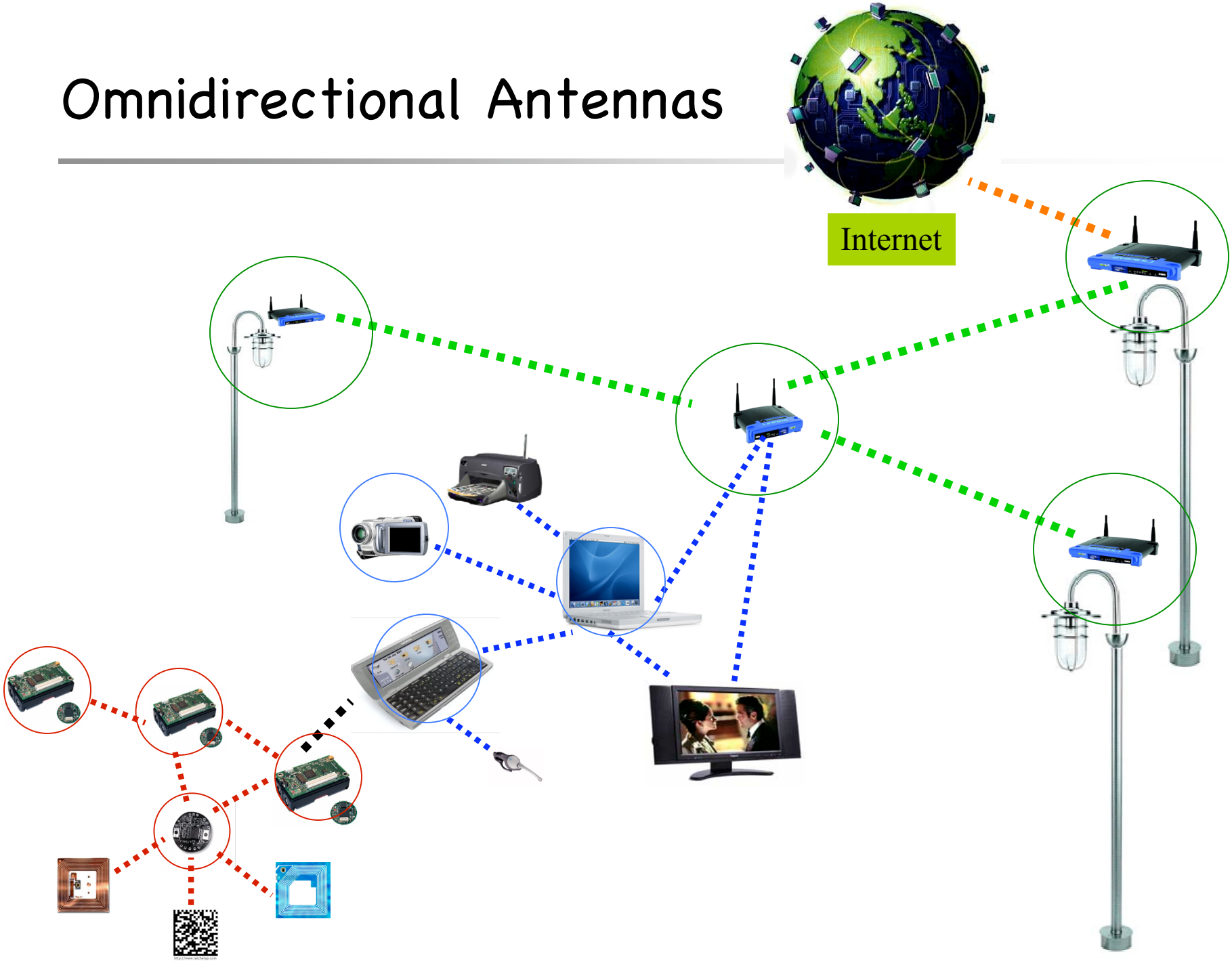




Summary

- Future = Dense wireless networks
  - Better interference management necessary
- Typical approach = Omni antennas
  - Inefficient energy management
  - PHY layer research needs be exploited

Omnidirectional Antennas

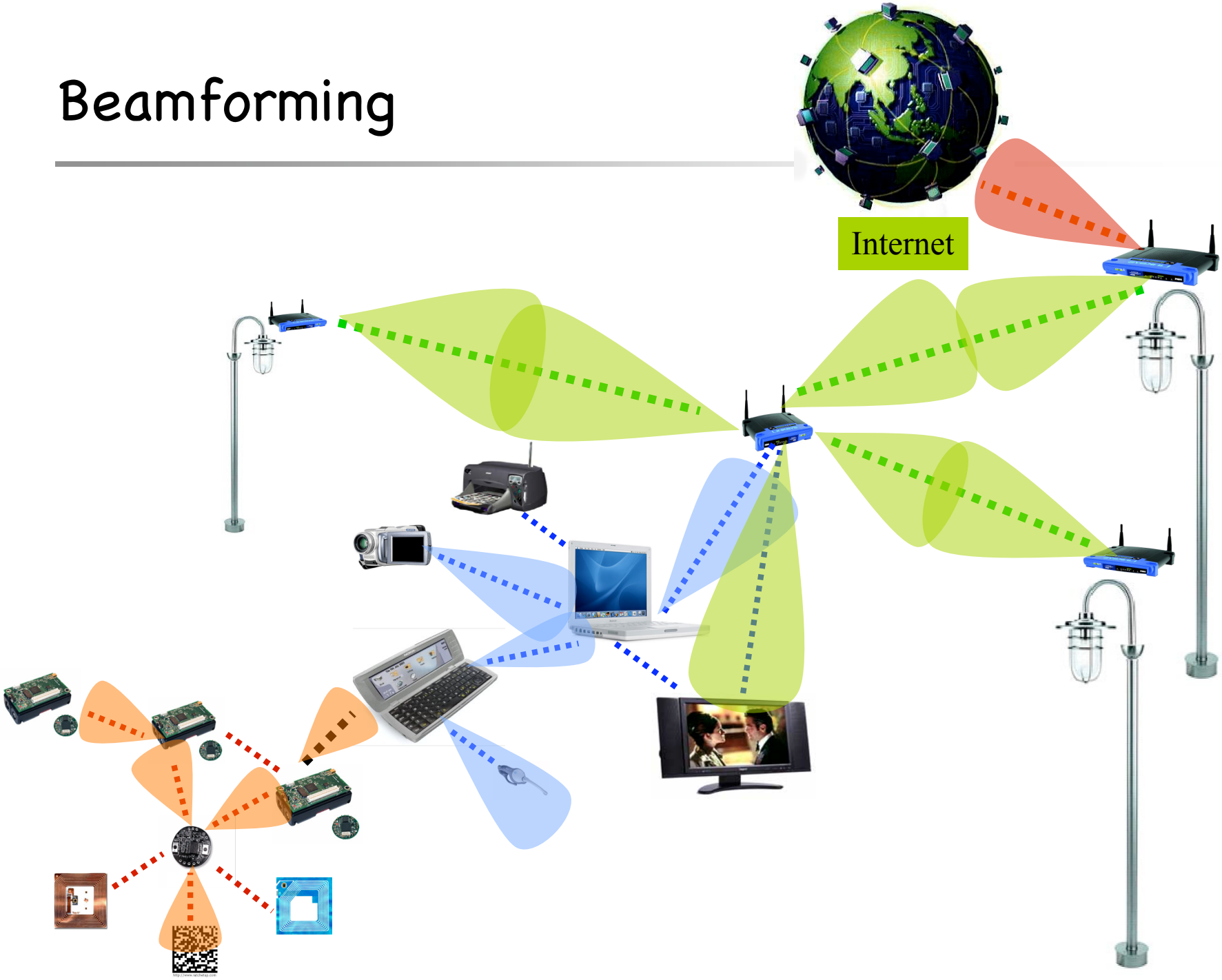


Summary

- Our focus = Exploiting antenna capabilities
  - Existing protocols not sufficient
- Our work
  - Identified several new challenges
    - Lot of ongoing research toward these challenges
  - Designed MAC, Network layer protocols
  - Theoretical capacity analysis
  - Prototype implementation

Our vision …

Beamforming



Much More ToDo's

- MAC/Routing/Security with MIMO
  - What are the right execution environments
- Can Spatial MUX and beamforming be combined
  - Observe environment, and prescribe optimal mode
- Combination of Smart and Omni antennas
  - Legacy users may remain omni -> can be network bottleneck
- What are the implications on infrastructure networks
  - MIMO, Beamforming in WiMAX, Thin WLANs, etc.
- Multicast support using beamforming/MIMO
  - Streaming audio, video, etc.

Thank You

for your patience

Collaborators

Nitin Vaidya (UIUC)

Xue Yang (Intel)

Ram Ramanathan (BBN)

Tetsuro Ueda (ATR Labs, Japan)

Other Research

- Mobile Computing
  - Using mobile phones as sensors (camera, mic, accelorometer …)
  - Browse and query the world under phone microscope
- Delay tolerant networks
  - Communication over diconnected networks
  - Exploiting physical mobility for communication
- Sensor Networks
  - Algorithms for joint compression and aggregation

Backup Slides

Other Work

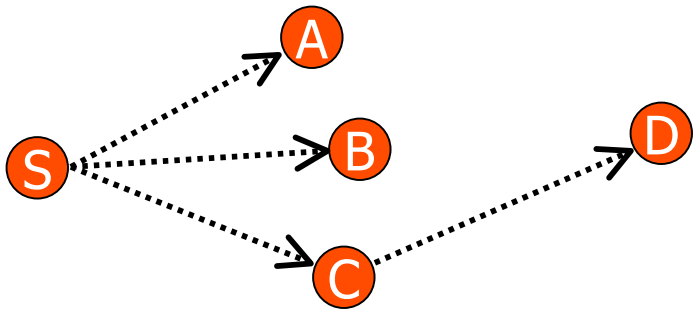
- Sensor Networks
  - Reliable broadcast [submitted]
  - Exploiting mobility [StoDis 05]
  - K-Coverage problems
- Location management in mobile networks
  - Distributed algorithms [IPDPS], [Mobihoc]
- Scheduling protocols for 802.11n
  - Combination of CSMA + TDMA schemes [WTS 04]

Future Work

- Next generation radios (software, cognitive)
  - PHY layer not be sufficient to harness flexibility
  - Example
    - When should a radio toggle between TDMA and CSMA ?
    - Dynamic channel access needs coordination
  - Higher layer protocols necessary for decisions

Future Work

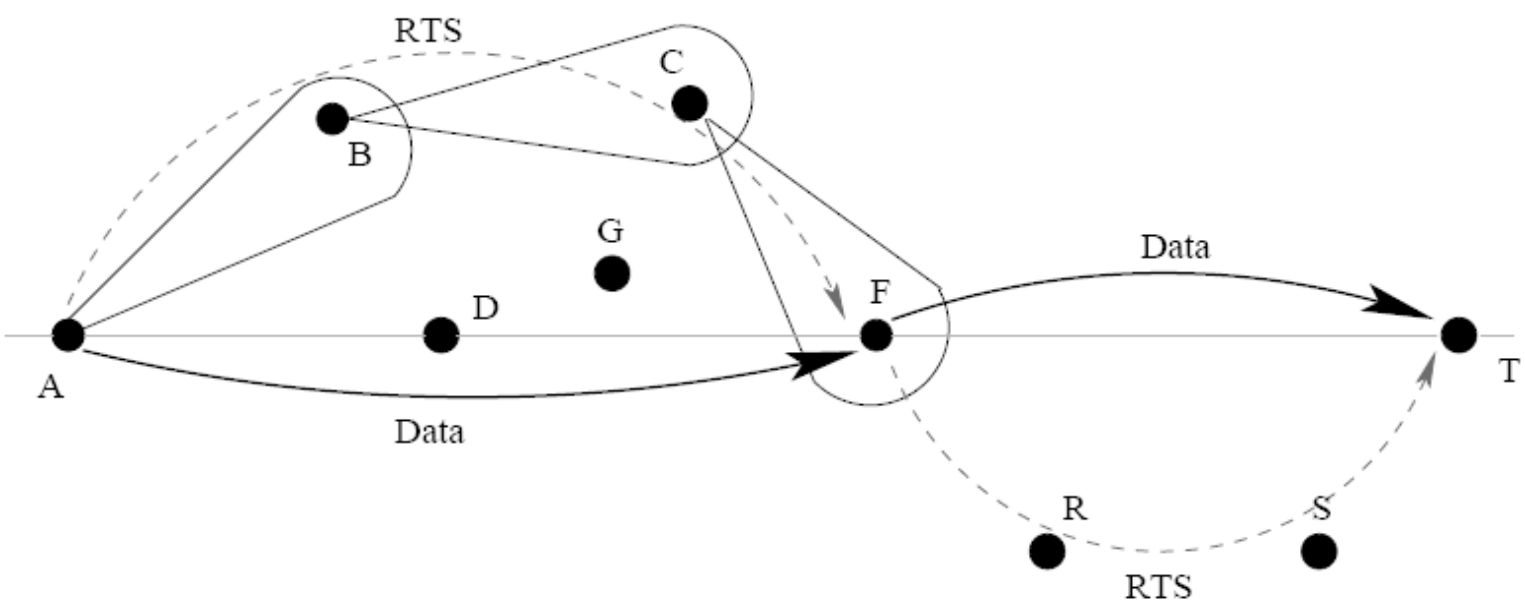
- Exploiting Diversity Opportunistically
  - Especially in the context of improving **reliability**
    - Link diversity
    - Route diversity
    - Antenna diversity
    - Channel diversity …



  - My previous work on **Anycasting** – a first step
  - I intend to continue in this direction

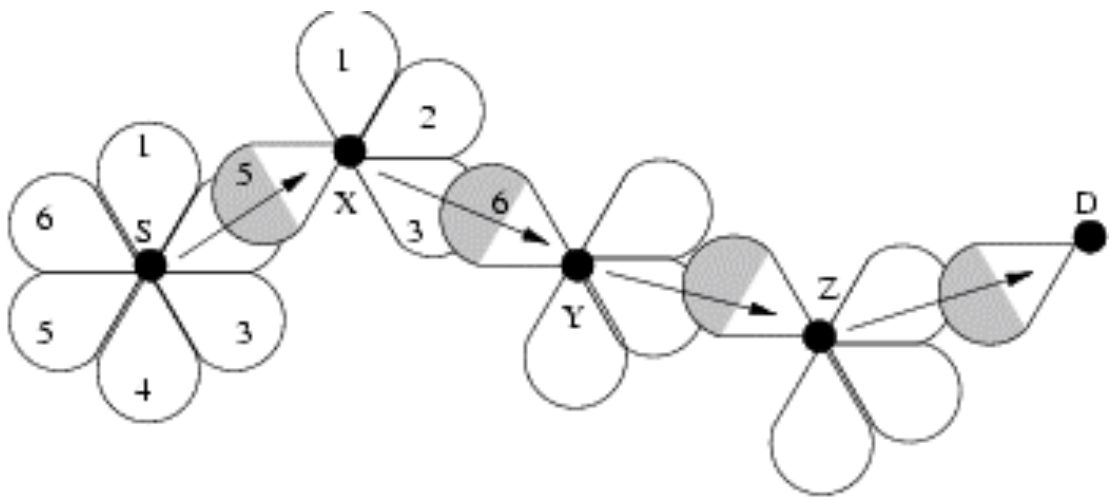
Enhancing MAC [Mobicom02]

- MMAC
  - Transmit multi-hop RTS to far-away receiver
  - Synchronize with receiver using CTS (rendezvous)
  - Communicate data over long links



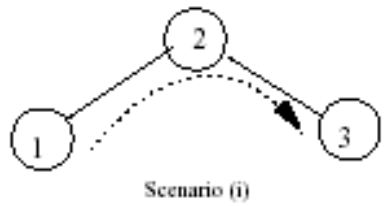
Routing with Higher Range [PWC03 Best Paper]

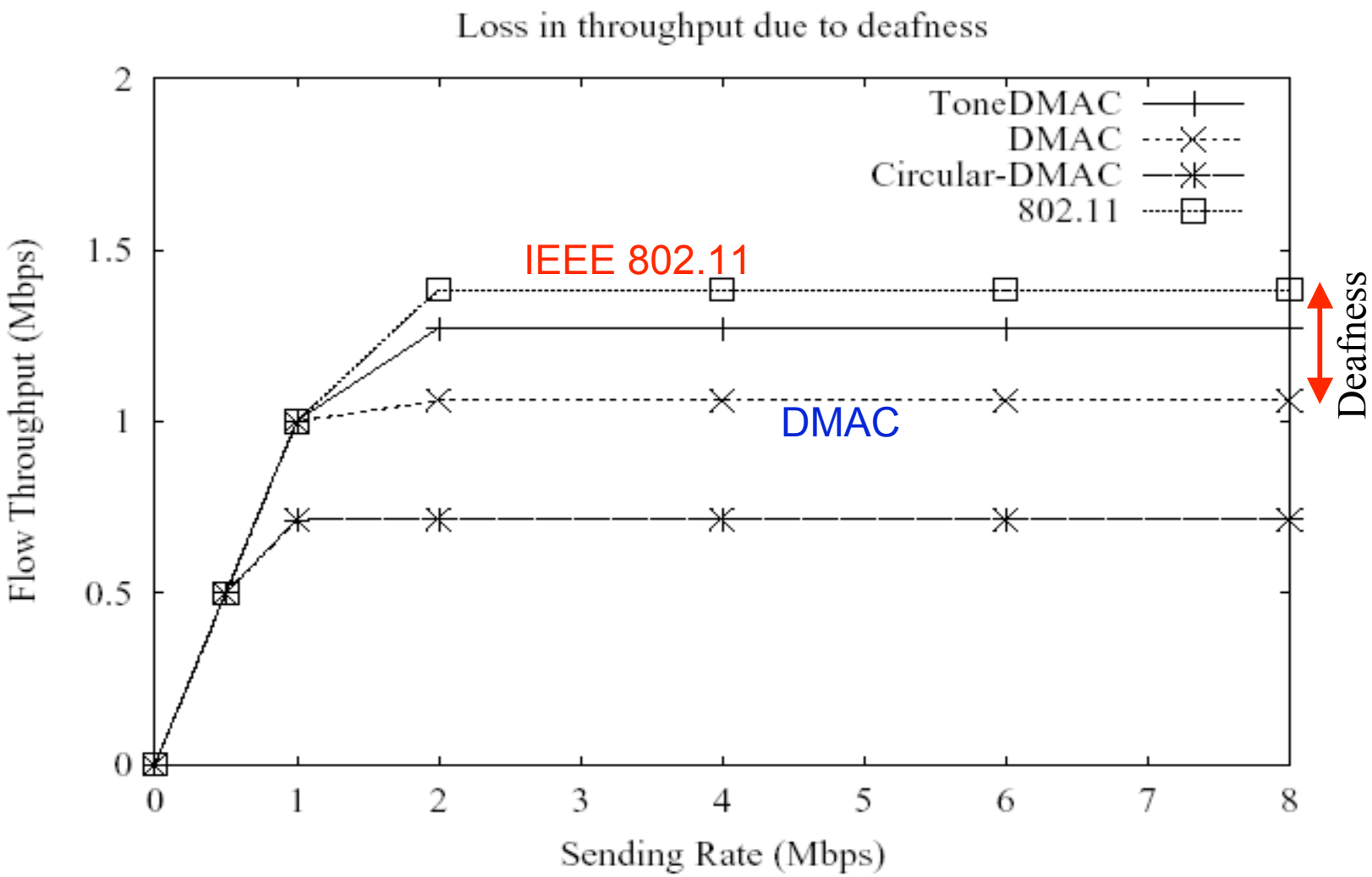
- Directional routes offer
  - Better connectivity, fewer-hop routes
- However, broadcast difficult
  - Sweeping necessary to emulate broadcast



- Evaluate tradeoffs → Designed directional DSR

2-hop flow


2
1
3
Scenario (i)

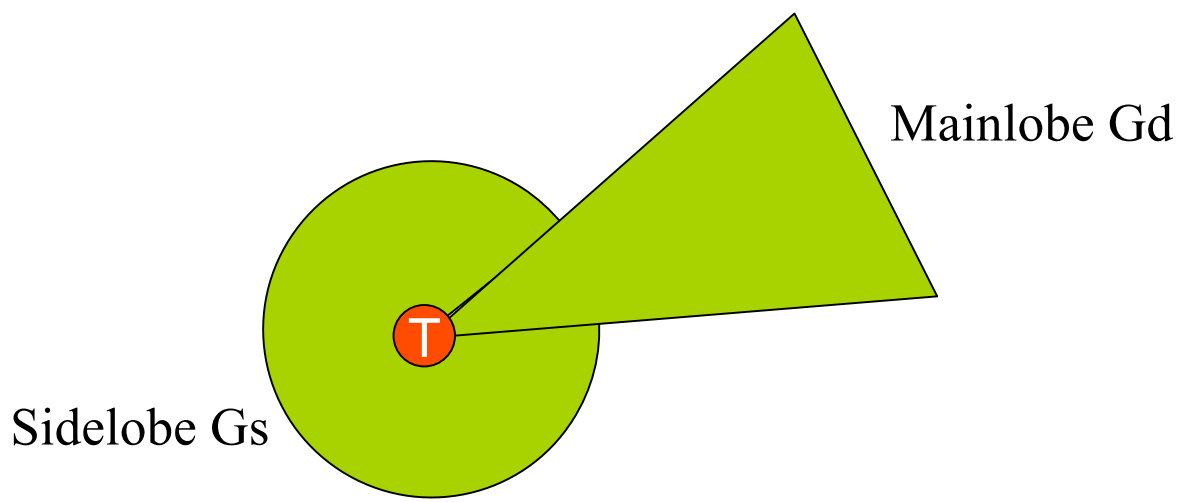

Loss in throughput due to deafness
ToneDMAC
DMAC
Circular-DMAC
802.11
IEEE 802.11
DMAC
Deafness
Flow Throughput (Mbps)
Sending Rate (Mbps)
0
0.5
1
1.5
2
0
1
2
3
4
5
6
7
8

Optimal Carrier Sense Threshold

- When sidelobe abstracted to sphere with gain

$$CS_{threshold-optimal} = \frac{\lambda^2 P_A G_d G_d}{4\pi r^\alpha (1 + (\frac{G_d}{G_s} SINR_{th})^{1/\alpha})^\alpha}$$

Provided, optimal CS threshold is above the Rx sensitivity threshold i.e., min {CS_calculate, RxSensitivity}



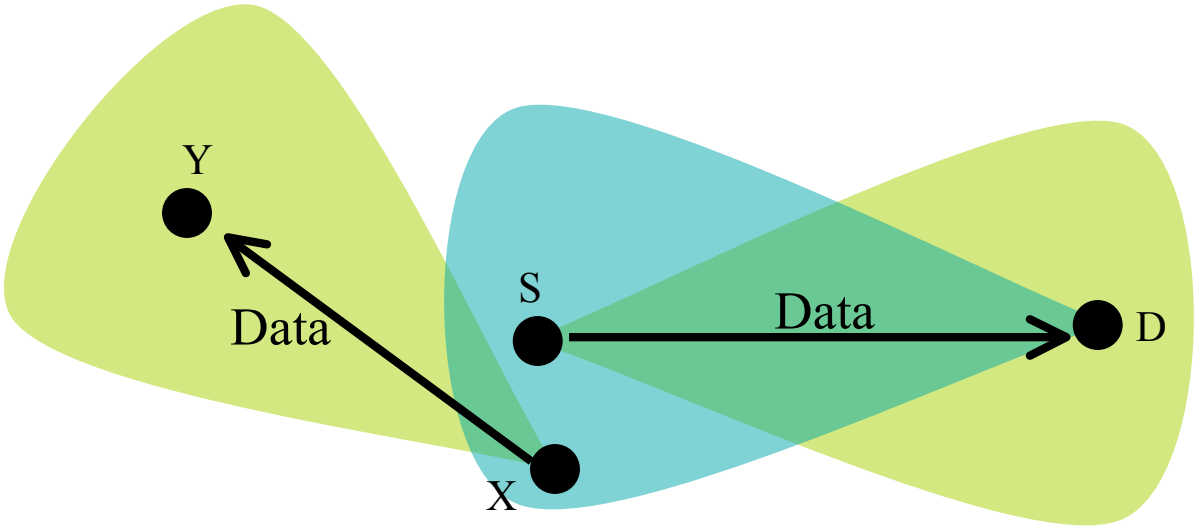
Commercial Antennas …

- Paratek (DRWin scanning smart antennas)
  - Beamforming in the RF domain (instead of digital)
  - Multiple simultaneous beams possible, each steerable
  - http://www.mobileinfo.com/news_2002/issue08/Paratek_Antenna.htm
- Motia Inc. (Javelin appliqué to 802.11 cards)
  - Blind beamforming in RF domain (< 2us, within pilot)
- CalAmps (DirectedAP offers digital beamforming)
  - Uses RASTER beamforming technology
  - http://www.calamp.com/pro_802_directedap.html

Commercial Antennas

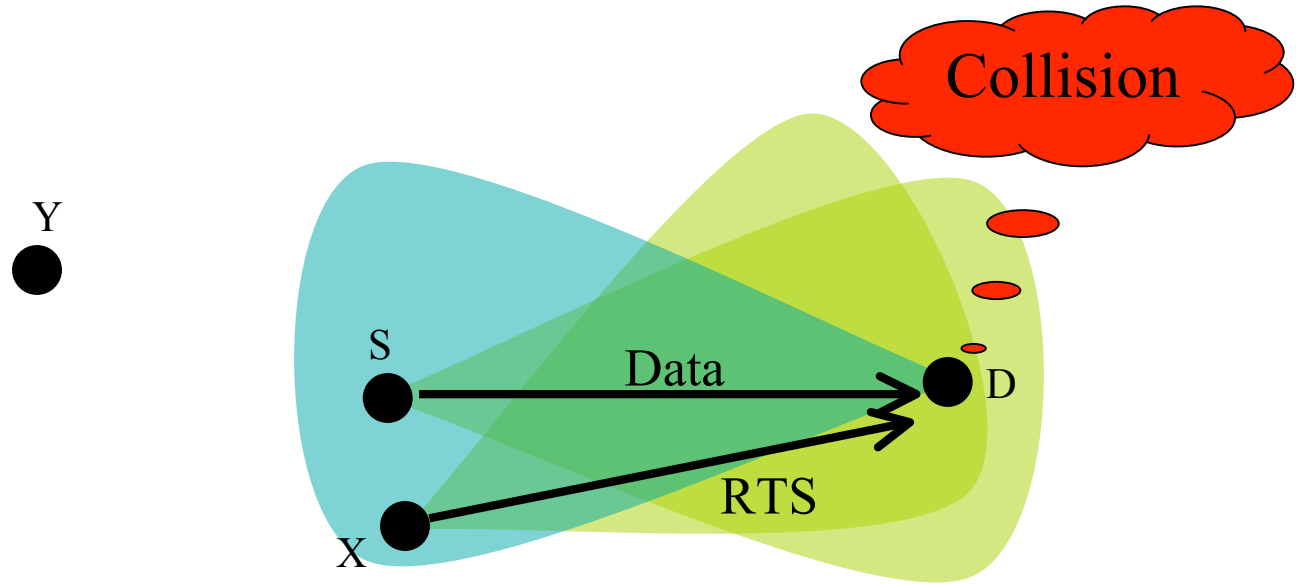
- Belkin (Pre-N smart antenna router – Airgo tech.)
  - Uses 3 antenna elements for adaptive beamforming
  - http://www.techonline.com/community/tech_group/37714
- Tantivy Communications (switching < 100 nanosec)
  - http://www.prism.gatech.edu/~gtg139k/papers/11-03-025r0-WNG-benefitsofSmartAntennasin802.11Networks.pdf

New Hidden Terminal Problem II



- While node pairs communicate
  - X misses D's CTS to S → No DNAV toward D

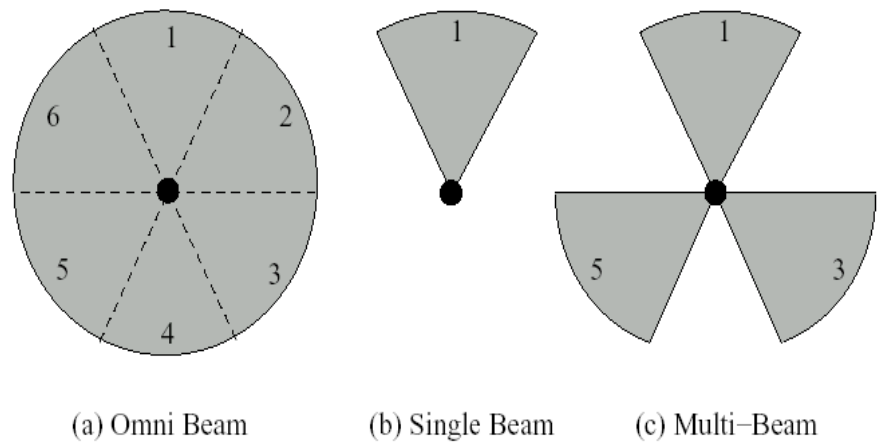
New Hidden Terminal Problem II



- While node pairs communicate
  - X misses D's CTS to S → No DNAV toward D
  - X may later initiate RTS toward D, causing collision

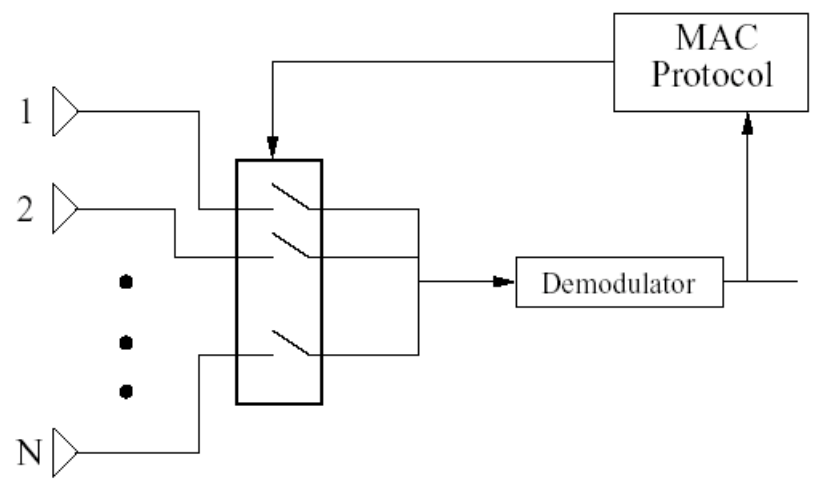
Abstract Antenna Model

- N conical beams
- Any combination of beams can be turned on



(a) Omni Beam (b) Single Beam (c) Multi–Beam

- Capable of detecting beam-of-arrival for received packet



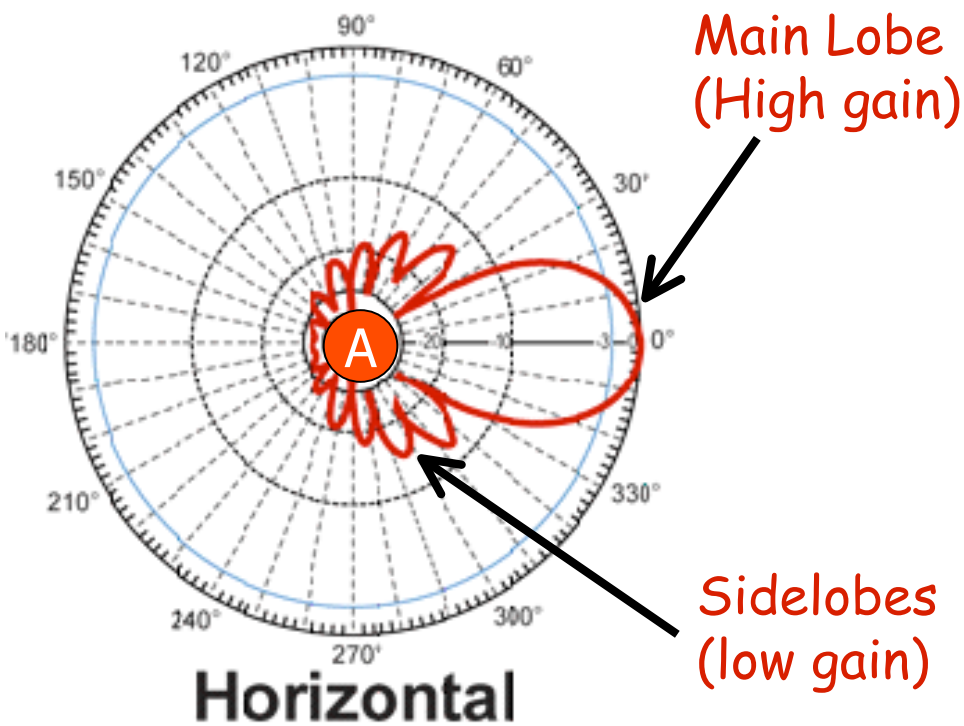
Antenna Systems

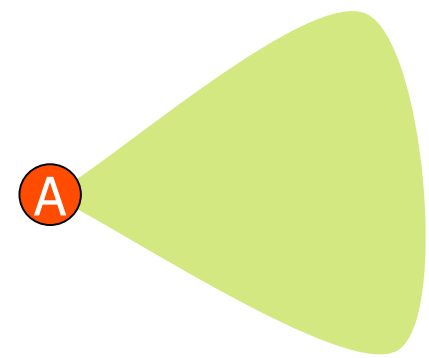
- Signal Processing and Antenna Design research
  - Several existing antenna systems
    - Switched Beam Antennas
    - Reconfigurable Antennas
    - MIMO Beamforming
    - MIMO Spatial Multiplexing
  - Many becoming commercially available

For example …

Antenna Beam

- Energy radiated toward desired direction

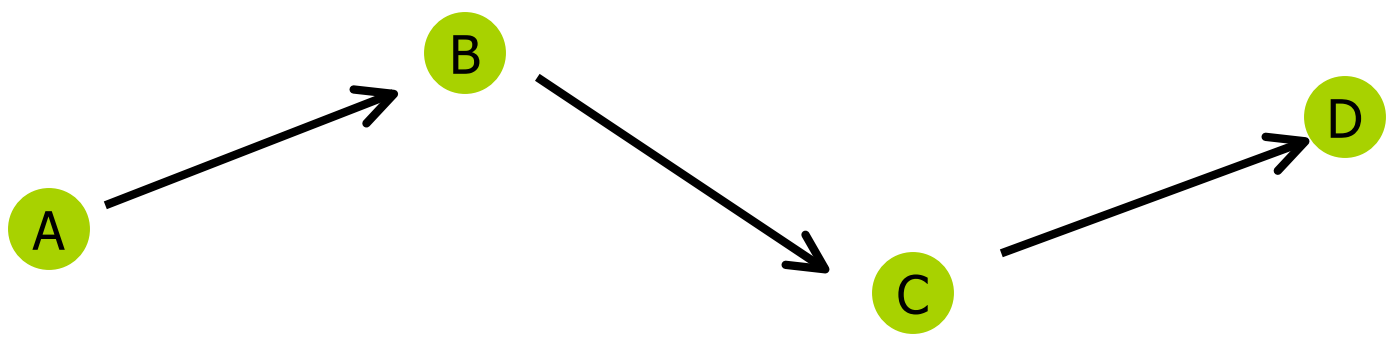




Pictorial Model

Wireless Multihop Networks

- Collection of wireless hosts
  - Relay packets on behalf of each other
  - Together form an arbitrary topology
  - May be connected to wired infrastructure



- 2 reasons to prefer multihop
  - Capacity and Power constraint

Wireless Multihop Networks

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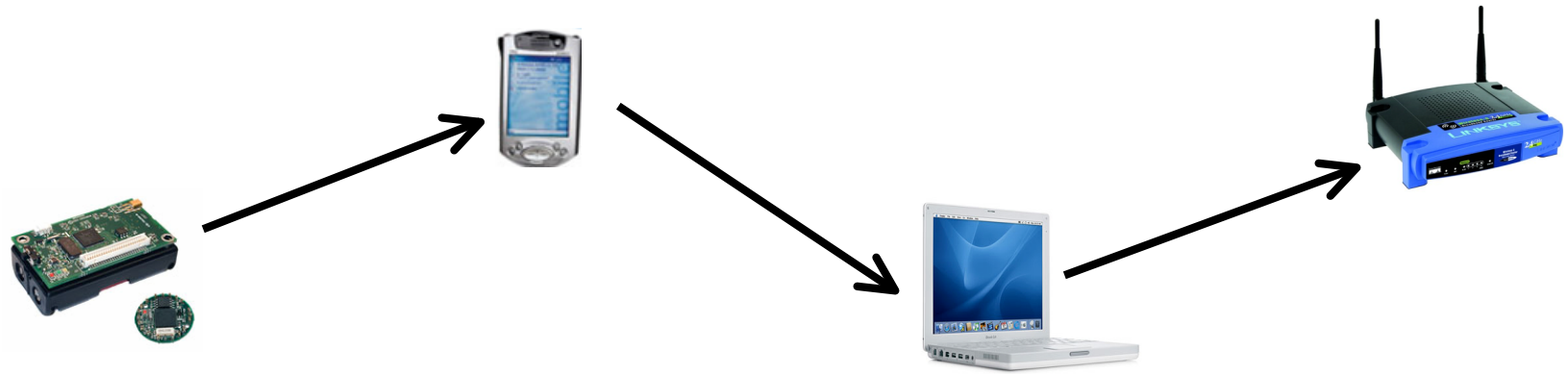


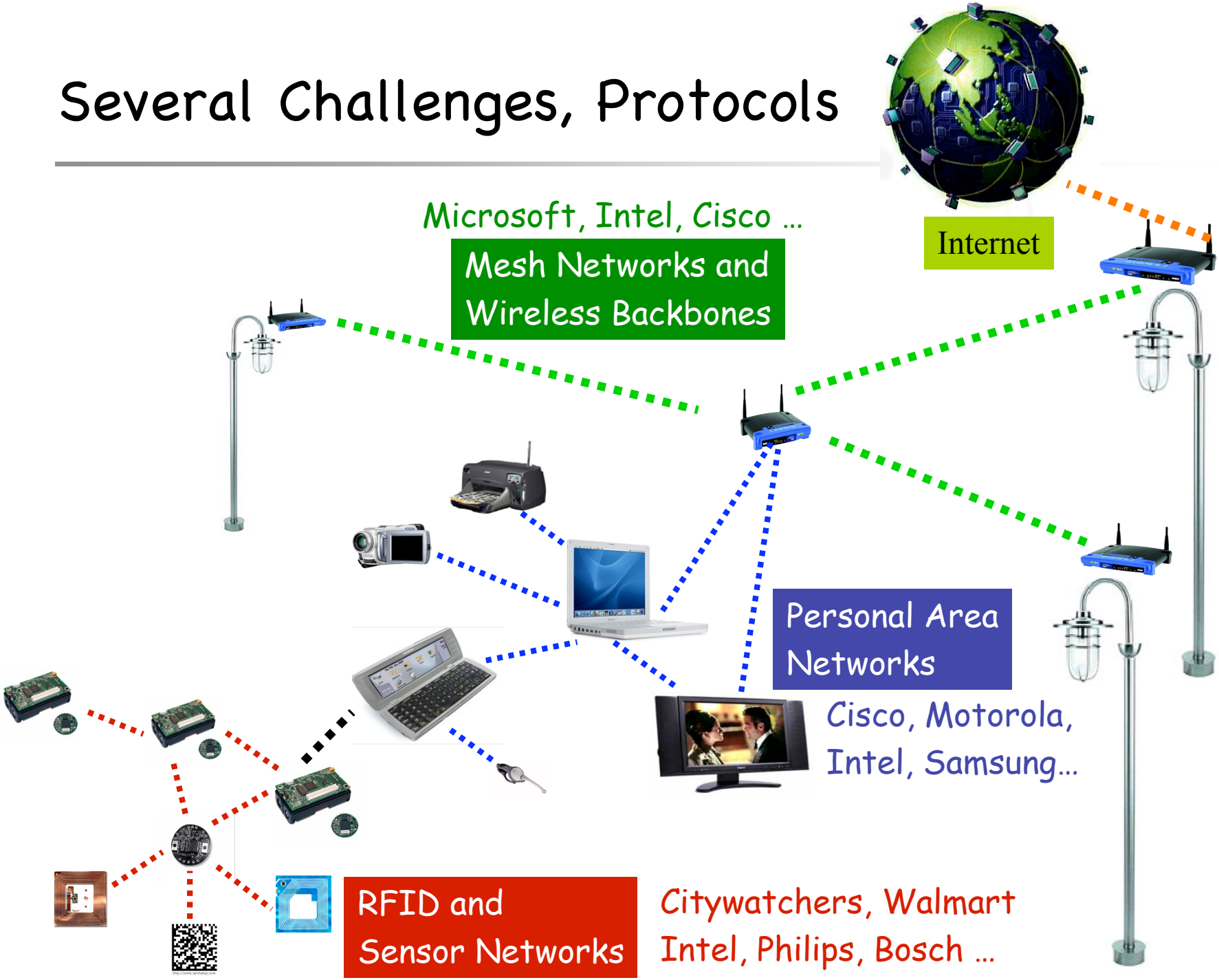
- 2 reasons to prefer multihop
  - Capacity and Power constraint

Applications

- Wide popularity in military
- Commercial applications emerging quickly

For Example …

Several Challenges, Protocols



Sustaining Growth

Difficult challenge

Independent innovations will no longer be enough

Near perfect synergy will be necessary across

Fields

Layers

Modules