OPTIMAL SPATIAL REUSE IN MOBILE AD HOC NETWORKS

Doctoral Dissertation Defense

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May 4, 2007

Overview

- Introduction
- Baseline Model
  - Radio Propagation Model
  - IEEE 802.11 DCF
- Analysis with baseline mode
  - Throughput Analysis
  - Spatial reuse with DCF
- Problem Statement
- Proposed Solutions
  - MASA
  - CAD
- Conclusions and Future work

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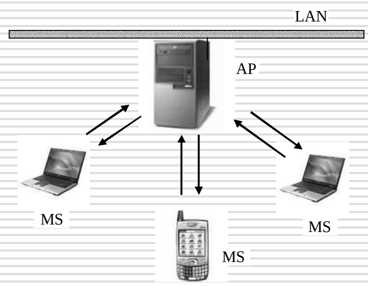
Wireless Networks Are Getting More and More Popular

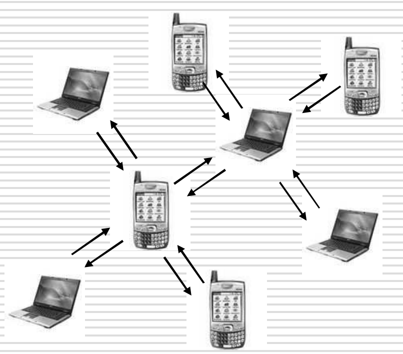
- Wireless Local Area Network (WLAN)
  - More than 80 percent of laptops in the US have equipped with Wi-Fi.
  - 88 percent of business professionals actively use this feature.
  - In the next five years a cumulative 940 million wireless devices are needed for use at home.
- Mobile Ad hoc NETwork (MANET)
  - Military battlefield
  - Emergency rescue in disaster field
  - Sensor network
  - Personal Area Network (PAN)

Wireless LAN (WLAN)



- MS+AP+LAN
- Infrastructured
- Centralized
- Single hop
- **No concurrent comm.**
- Standard: 802.11 DCF

Mobile Ad hoc NETwork (MANET)



- MS only
- Infrastructure-less
- Distributed
- Multiple hop
- **Concurrent comm.**
- Standard: 802.11 DCF?

Motivation, Problem and Basic Idea

- Motivation: Reconsider 802.11 DCF in MANET
  - Multiple hop → Concurrent communications → Spatial reuse
- Problem
  - Concurrent communications → Interference → Collisions
- Basic Idea
  - Encourage concurrent communications
  - Address collision issues

Overview of Proposed Solutions

- MASA (Multiple Access with Salvation Army)
  - Encourage more concurrent communications while salvaging collided packets.
  - Post-collision mechanism
- CAD (Collision-Aware DCF)
  - Adaptively encourage more concurrent transmissions via predicting collisions.
  - Pre-collision mechanism

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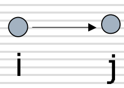
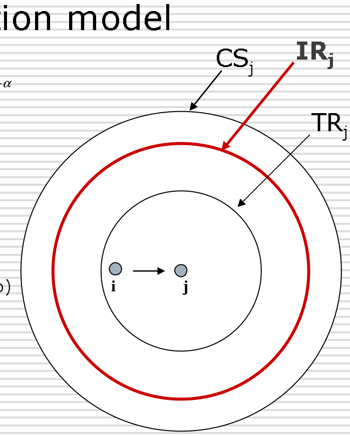
Radio Propagation Model

- Two-ray ground propagation model



$P_r = P_{t,i}\gamma_{ij}$ $\gamma_{ij} \propto d^{-\alpha}$



- Signal Reception

$P_r = P_{t,i}\gamma_{ij} \geq \mathrm{P_{tr}}$ (P_{tr}: Receive sensitivity)

$$SIR = \frac{P_{t,i}\gamma_{ij}}{N_0 + \sum_{k \neq i} P_{t,k}\gamma_{kj}} \geq z_0$$ (z_0: Capture ratio)

- Signal sense

$P_r = P_{t,i}\gamma_{ij} \geq \mathrm{P_{cs}}$ (P_{cs}: Carrier sense threshold)

IEEE 802.11 DCF

- Distributed Coordination Function
- MAC Mechanisms
  - Carrier Sense Multiple Access (CSMA)
  - Collision Avoidance (CA) (instead of CD)
  - Inter-Frame Space (IFS)
  - Retransmission
  - Exponential Backoff
  - Frame exchange

IEEE 802.11 DCF

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- MAC Mechanisms
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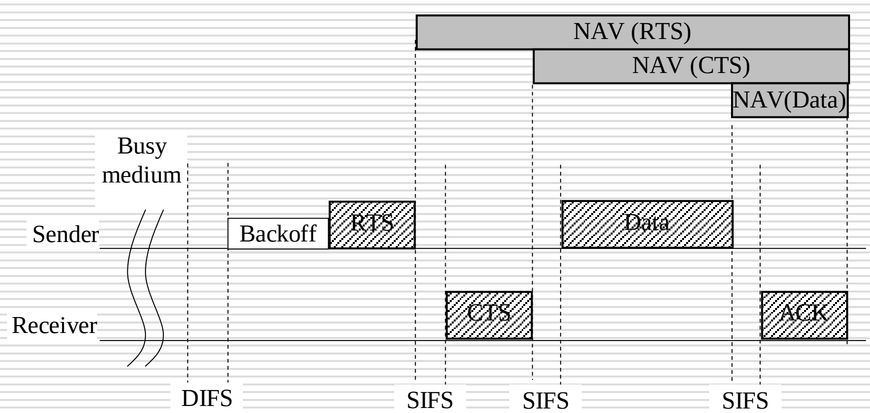
  - Retransmission
  - Exponential Backoff
  - **Frame exchange**

Carrier Sense Multiple Access (CSMA)

- Physical Carrier Sense (PCS)
  - Medium is considered busy if signal strength is above a pre-configured threshold, called CS threshold.
- Virtual Carrier Sense (VCS)
  - Network Allocation Vector (NAV)

    Medium is considered busy if NAV is greater than zero.

Frame Exchange in DCF



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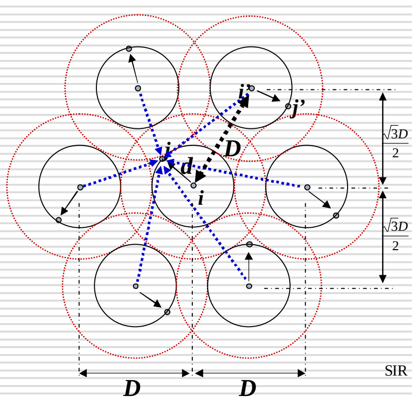
Throughput Analysis



- Distances from 6 interferers are

$D-d$ $\quad \sqrt{D^2+d^2-Dd}$ $\quad \sqrt{D^2+d^2-Dd}$

$\sqrt{D^2+d^2+Dd}$ $\quad \sqrt{D^2+d^2+Dd}$ $\quad D+d$

- Distance between two adjacent senders satisfies

$$\mathrm{SIR} = \frac{P_r(d)}{P_r(D-d)+2P_r\left(\sqrt{D^2+d^2-Dd}\right)+2P_r\left(\sqrt{D^2+d^2+Dd}\right)+P_r(D+d)} \geq z_0$$

Throughput Analysis (cont'd)

- Maximum Throughput in an $L \times L$ square network
  - $d_{cs} < D_{min}$, the senders must be separated by D_{min} to reach the maximum overall network throughput. That is

$$T_e = \frac{\sqrt{6}Lbd}{\left(\sqrt[\alpha]{6z_0}\,d\right)^2} = \frac{\sqrt{6}Lb}{\left(\sqrt[\alpha]{6z_0}\right)^2} \times \frac{1}{d}$$

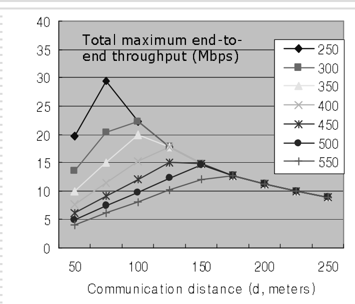
  - $d_{cs} \geqslant D_{min}$ the senders must be separated by d_{cs}. The throughput is

$$T_e = \frac{\sqrt{6}Lbd}{d_{CS}^{\,2}} = \frac{\sqrt{6}Lb}{d_{CS}^{\,2}} \times d$$

Throughput Analysis (cont'd)

- How d and d_{cs} affect Maximum Throughput?

(b=1Mbps, L=10km, z_0=10dB, α=4.0)



With short-distance communication, smaller CS range can achieve a higher throughput.

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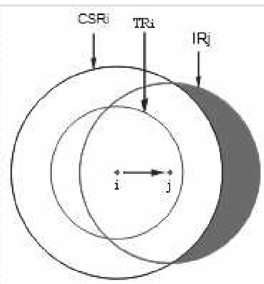
Spatial Reuse with a Single Frame Transmission

- Hidden terminal problem
  - Vulnerable Space (VS)
    Nodes within VS can not sense ongoing communication but can cause collision to receiver.



$$VS = CP_j \cap \overline{CS_i}$$

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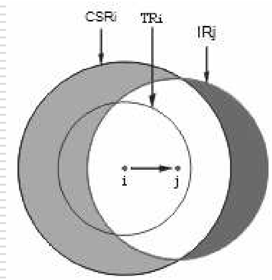
Spatial Reuse with a Single Frame Transmission

- Hidden terminal problem
  - Vulnerable Space (VS)

    Nodes within VS can not sense ongoing communication but can cause collision to receiver.
- Exposed terminal problem
  - Wasted Space (WS)

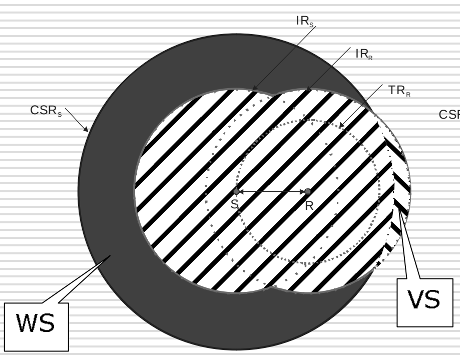
    Nodes within WS can sense ongoing communication but will not cause collision to receiver.



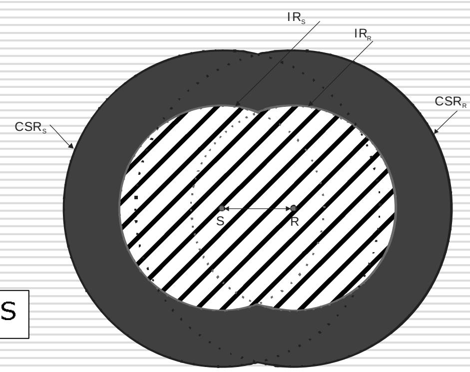
$$VS = CP_j \cap \overline{CS_i}$$
$$WS = CS_i - VS = CS_i - CP_j$$

Spatial Reservation with DCF Frame Exchanges

- While RTS and CTS are Transmitted



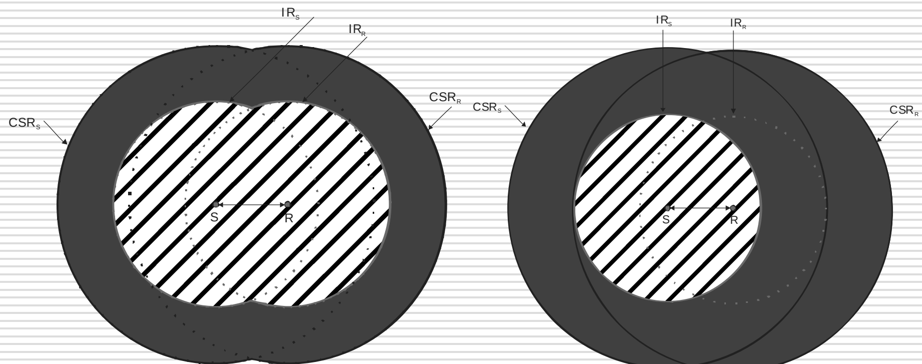
Transmitting RTS



Transmitting CTS

Spatial Reservation with DCF Frame Exchanges (Cont'd)

- While DATA and ACK are Transmitted



Transmitting DATA

Transmitting ACK

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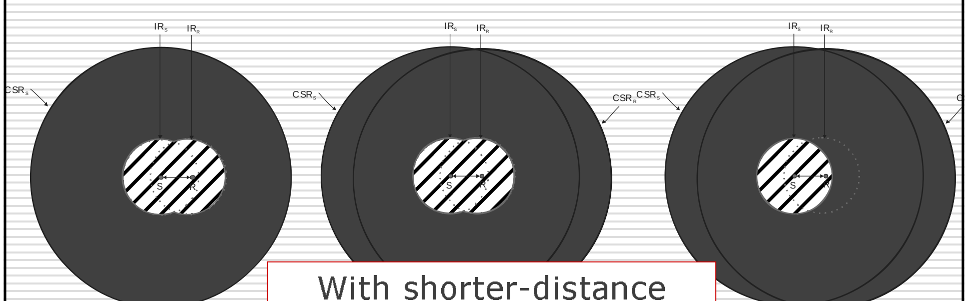
Spatial Reservation with DCF Frame Exchanges (Cont'd)

- With shorter communication distance



Transmitting RTS

With shorter-distance communication, DCF wastes more spatial area.

Transmitting ACK

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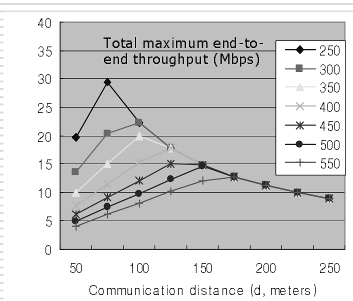
Problem Statement

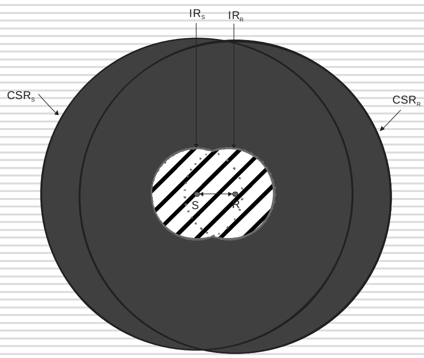


With short-distance communication, smaller CS range can achieve a higher throughput.

Is it possible to use lower CS range and short-distance communication to improve the performance?

MASA

Problem Statement (Cont'd)



With short-distance communication, DCF wastes more spatial area.

Is it possible to only reserve the spatial area that is required?

CAD

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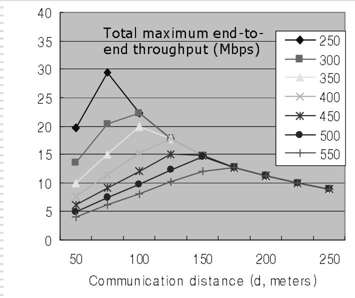
Recall Throughput Analysis



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Is it possible to use lower CS range and short-distance communication to improve the performance?

MASA

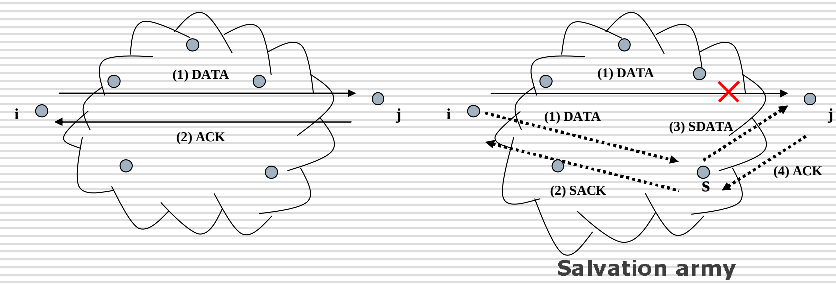
Proposed Solution: MASA

- MASA (Multiple Access with Salvation Army)
  - Adopts low CS range to reduce WS
    - Encourages more concurrent communications
    - More interferences and collisions
  - Salvages collided packets
    - Automatically breaks a long-distance link into two short-distance links, which are more robust against interference

MASA Algorithm

No collision

Collision at receiver



Benefits and Issues in MASA

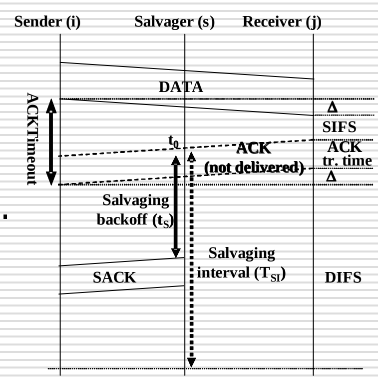
- Benefits
  - Makes progress toward the receiver
  - Offloads sender's pending packets as quickly as possible and thus, reduces queue size and packet delay
  - Reduces false alarms for live link and thus, reduces routing overhead
- Issue
  - Who to become the salvager?

Who're Eligible to Salvage?

- Must be a neighbor of sender
  - Receive sender's DATA packet
- Must be a neighbor of receiver
  - Recognize collision at the receiver
- Should make progress
  - Salvager is nearer to receiver than sender.
- Should have no pending packets
  - Too busy to help
  - Balancing network traffic

Who is Elected among Candidates?

- Based on "salvaging backoff"
- Starting salvaging timer once recognizing collision.
- Salvaging collided packet once timer expires.
- Giving up salvaging if hearing other salvaging actions.



$$t_S = q_{ji} / q_{js} \times T_{SI}$$

Simulation Environment

System parameters
- Simulation time: 900s
- 100 nodes in 300×1500 m²

Mobility parameters
- Random waypoint mobility model
- Maximum speed: 5m/s

Simulator

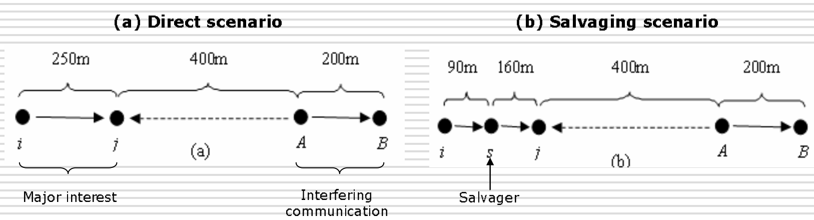
ns2 2.27 **with modification for cumulative interference and signal capture**

Traffic parameters
- 40 CBR connections
  Packet rate: 3 packets/s Packet size: 256 bytes
- 40 — 100 TCP connections

Other parameters
- AODV routing
- Two-ray ground propagation model
- 250m TR range; 350m and 550m CS range for MASA and DCF, respectively

Simulation with A Single Interferer

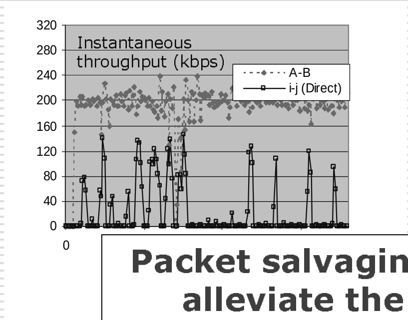
- Simulation scenario

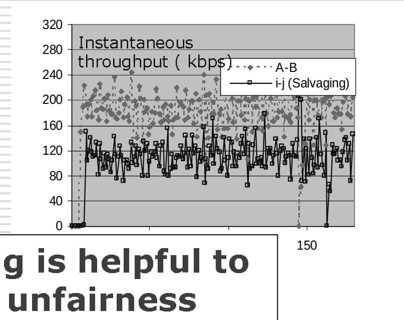


- Simulation parameters
  - Simulation time: 180s
  - Transmission range: 250m
  - Propagation model: two-ray ground propagation channel
  - Packets: 512 bytes CBR or TCP packets
  - Data rate: 2Mbps

Simulation Results with CBR Traffic

(a) Direct scenario **(b) Salvaging scenario**





Unfair ... gregate

Packet salvaging is helpful to alleviate the unfairness problem and to improve the performance.

Simulation with Multiple Interferers

DCF2

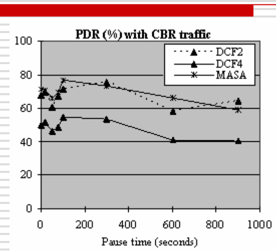
DCF with two-way handshake (without RTS/CTS)

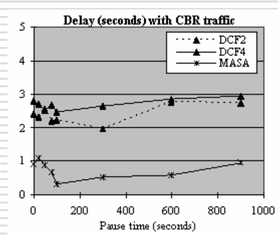
DCF4

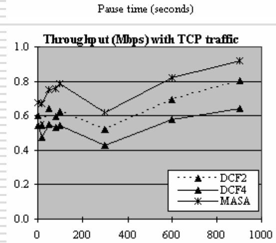
DCF with four-way handshake (with RTS/CTS)

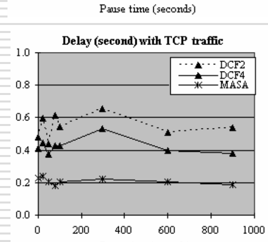
MASA

With two-way handshake (without RTS/CTS)

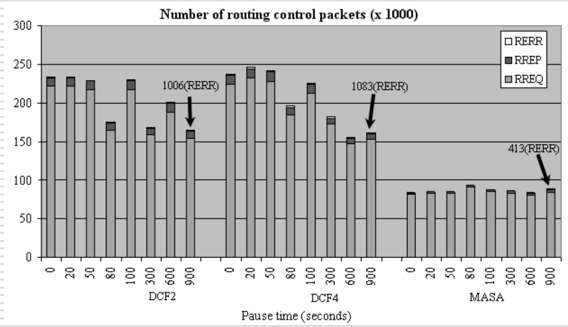


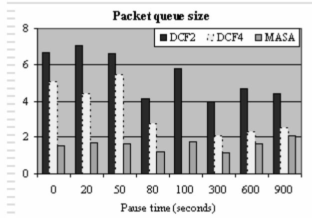




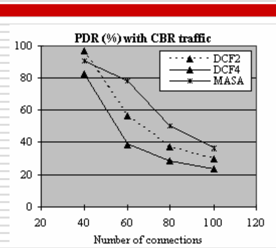


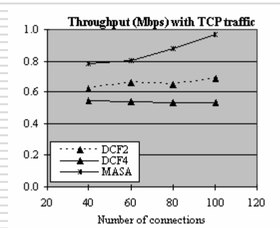
Routing Overhead and Packet Queue Size

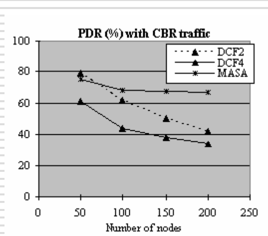


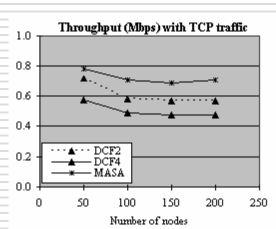


Simulation Results with Traffic Intensity and Node Density









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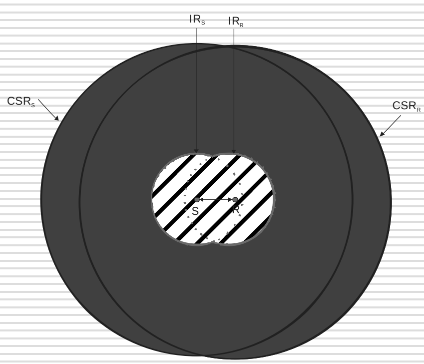
Recall Spatial Reservation with DCF



With short-distance communication, DCF wastes more spatial area.

Is it possible to only reserve the spatial area that is required??

CAD

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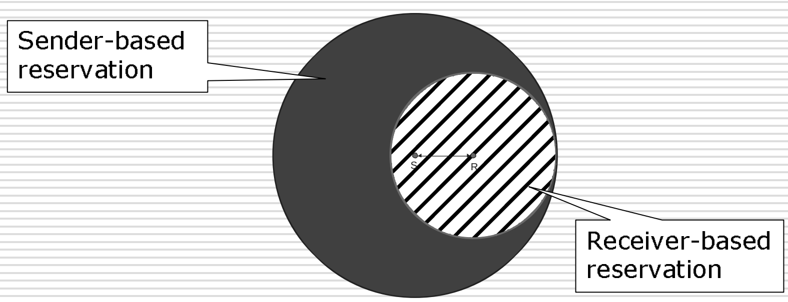
Proposed Solution: CAD

- CAD (Collision-Aware DCF)
- Estimating optimal reservation requirements
  - Spatial requirement
  - Time requirement
- Distributing reservation requirements
  - Piggybacking on transmitting packets
  - Using the PLCP header
- Receiving and handling reservation requirements
  - DO NOT cause collision to ongoing transmissions
  - DO NOT let its own transmission to be collided
- **A key question is how to estimate spatial and time requirement?**

Idea of CAD Reservation

- Receiver-based reservation



- Making reservation for the next frame

Receiver-based Reservation with Frame Exchanges

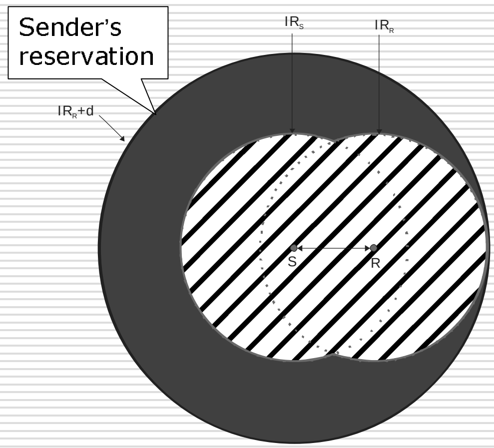
- How to make a receiver-based reservation?
  - In RTS, Sender makes reservation for CTS reception.
  - In CTS, Receiver makes reservation for DATA reception.
  - In DATA, Sender makes reservation for ACK reception.
  - In ACK, Receiver does NOT make any reservation.
- Especially in RTS, sender needs to make reservation for RTS reception.

Spatial and Time Reservation

Frame	Time reservation	Spatial reservation (radius)
RTS	T_{RTS}+SIFS+T_{CTS}+ Δ	d + IR_R
CTS	T_{CTS}+SIFS+T_{DATA}+ Δ	IR_R
DATA	T_{DATA}+SIFS+T_{ACK}+ Δ	IR_S
ACK	0	0

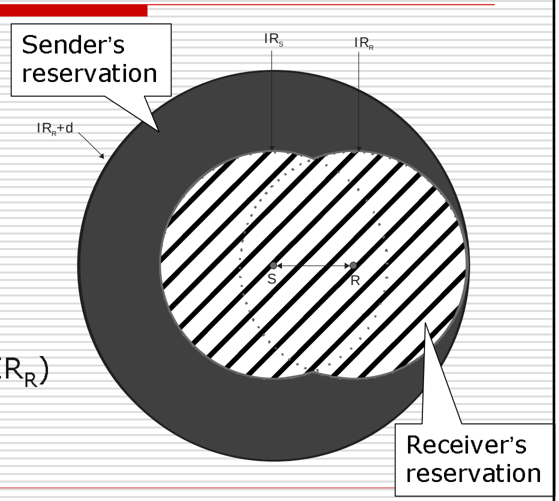
Spatial Reservation with CAD (While RTS is transmitted)

- Receiver makes none reservation
  $\varnothing$
- Sender makes reservation
  $Area(d+IR_R)$
- Overall reservation
  $\varnothing \cup Area(d+IR_R) = Area(d+IR_R)$



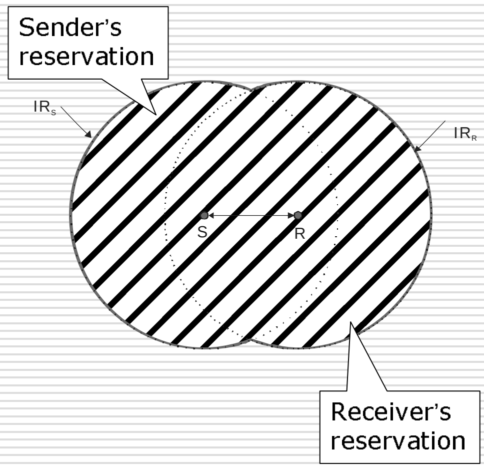
Spatial Reservation with CAD (While CTS is transmitted)

- Sender's reservation made in RTS is still effective.
  $Area(d+IR_R)$
- Receiver makes reservation
  $Area(IR_R)$
- Overall reservation
  $Area(d+IR_R) \cup Area(IR_R) = Area(d+IR_R)$



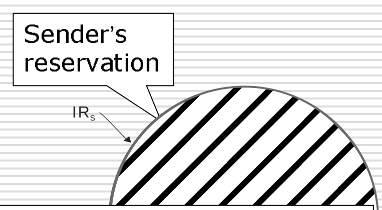
Spatial Reservation with CAD (While DATA is transmitted)

- Receiver's reservation made in CTS is still effective.
  Area(IR_R)
- Sender makes reservation
  Area(IR_S)
- Overall reservation
  Area(IR_R) ∪ Area(IR_S)



Spatial Reservation with CAD (While ACK is transmitted)

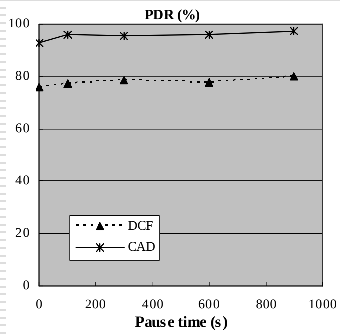
- Receiver makes none reservation
  ∅
- Sender's reservation made in DATA is still effec
  Area
- Over
  ∅ ∪ A

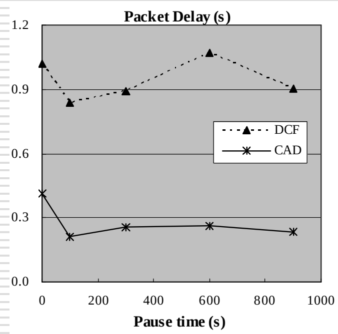


While RTS and CTS are transmitted, CAD reserves less spatial area than DCF. While DATA and ACK are transmitted, CAD only reserves the required spatial area (Both VS and WS are gone)

Simulation Results

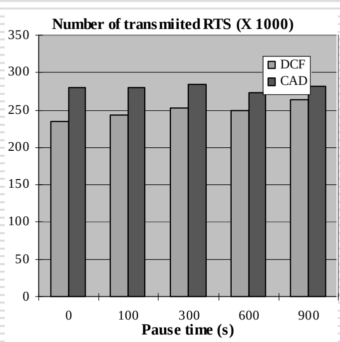
- Performance with mobility

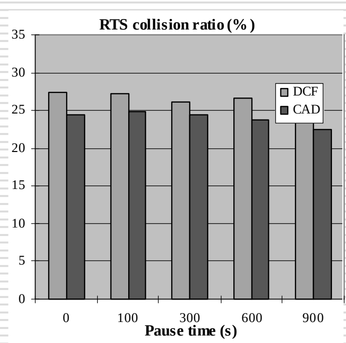




Simulation Results (Cont'd)

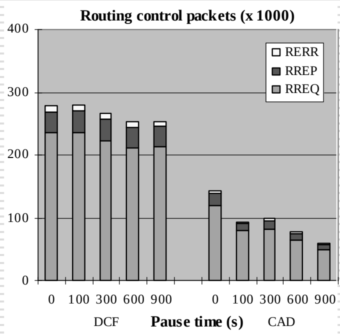
- Transmission Concurrency and Collision

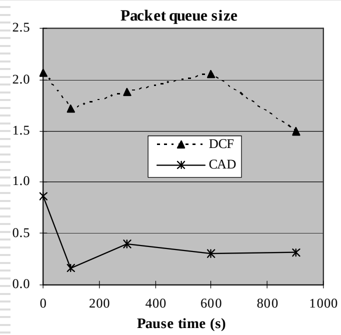




Simulation Results (Cont'd)

- Routing overhead and packet queue





Overview

- Introduction
- Baseline Model
  - Radio Propagation Model
  - IEEE 802.11 DCF
- Analysis with baseline mode
  - Throughput Analysis
  - Spatial reuse with DCF
- Problem Statement
- Proposed Solutions
  - MASA
  - CAD
- **Conclusions and Future work**

Conclusions

- MASA
  - MASA improves network performance regardless of mobility, scalability (traffic intensity and node density).
  - In particular, it reduces packet delay significantly.
  - MASA is more useful in dense networks and in delay-sensitive applications.
- CAD
  - CAD encourages more concurrent transmissions but at the same time avoids collisions more effectively than DCF.
  - The benefits of CAD come from
    - Receiver-based reservation.
    - Embedding the reservation requirements in PLCP header makes more nodes be informed and be aware of collisions to ongoing communications.

Future Work

- In MASA use deterministic algorithm to elect salvager
- Apply MASA algorithm in sensor networks
- Combine CAD with TPC and TRC schemes
- Combine MASA and CAD

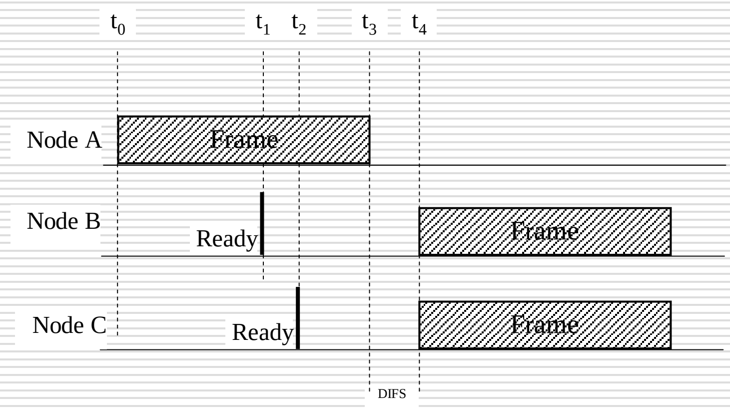
Research Publications

- C. Yu, K. G. Shin, and **L. Song**, "Link Layer Salvaging for Making Routing Progress in Mobile Ad Hoc Networks," *The Conference on Mobile Ad Hoc Networking and Computing (Six ACM International Symposium)*, 2005. (Acceptance ratio 14%)
- C. Yu, K. G. Shin, and **L. Song**, "Maximizing Communication Concurrency via Link-Layer Packet Salvaging in Mobile Ad Hoc Networks," IEEE Trans. Mobile Computing, Vol. 6, pp. 449-462, 2006
- **L. Song** and C. Yu, "Improving Spatial Reuse with Collision-Aware DCF in Mobile Ad Hoc Networks," 35th International Conference on Parallel Processing (ICPP), 2006.
- **L. Song** and C. Yu, "Minimizing Spatial and Time Reservation with Collision-Aware DCF in Mobile Ad Hoc Networks," (Submitted to the journal Ad Hoc Networks in 2006).

THANK YOU !

Questions?

Problem of Pure CSMA - Collision

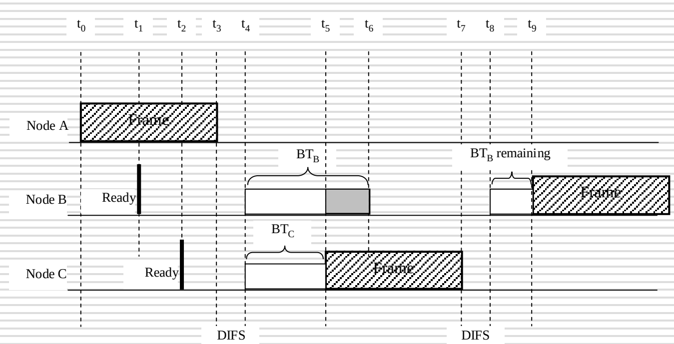


DIFS: DCF Interframe Space (50us)

Collision Avoidance

- Backoff

  Backoff Time = Rand (0, CW) × Slot Time

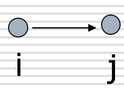


Retransmission and Exponential Backoff

- Retransmission
  - Retransmission is scheduled if ACK is not received.
- Exponential Backoff
  - CW starts from CW_{min}
  - Every time a retransmission happens CW is doubled except CW reaches CWmax

Radio Propagation Model

- Two-ray ground propagation model

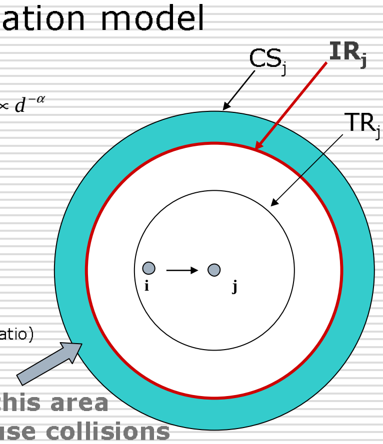


$P_r = P_{t,i}\gamma_{ij}$ $\gamma_{ij} \propto d^{-\alpha}$

- Reception Model

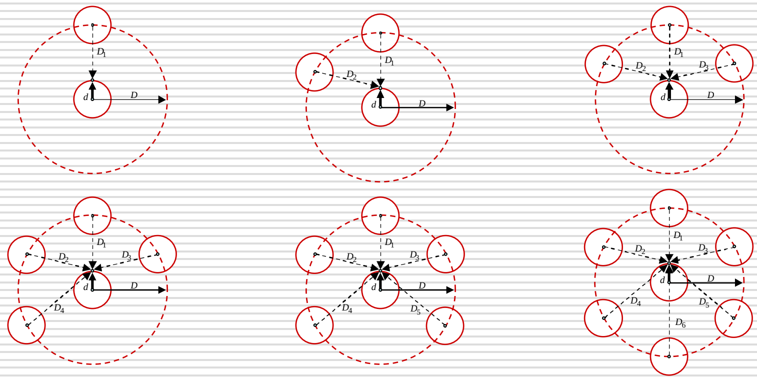
$P_r = P_{t,i}\gamma_{ij} \geq P_0$ (P_0: Receive Sensitivity)

$$SIR = \frac{P_{t,i}\gamma_{ij}}{N_0 + \sum_{k \neq i} P_{t,k}\gamma_{kj}} \geq z_0$$ (z_0: capture ratio)



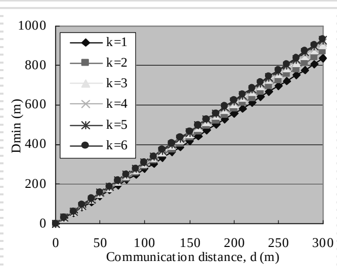
Interference Range (IR)

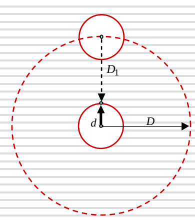
- Worst-Case Interference Scenarios



$D_1 = D - d$ $D_2 = D_3 = \sqrt{D^2 + d^2 - Dd}$ $D_4 = D_5 = \sqrt{D^2 + d^2 + Dd}$ $D_6 = D + d$

Interference Range(cont.)





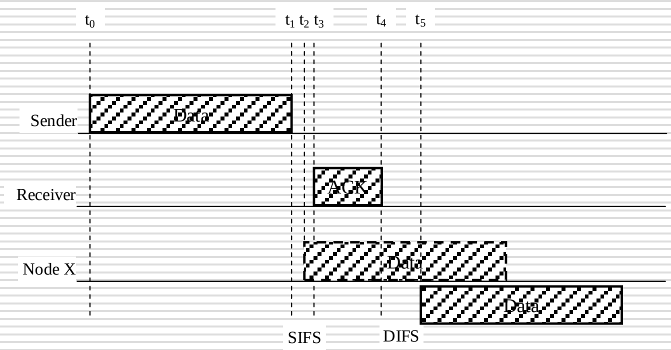
- Communication distance d almost dominates the influence.
- Use k=1 to make estimation.

$$D_{\min} = \left(\sqrt[4]{Z_0} + 1\right) \cdot d$$

$$\mathrm{IR} = D_{\min} - d = \sqrt[4]{Z_0} \cdot d$$

Inter-Frame Space

- Shortest IFS (SIFS)
- PCF IFS (PIFS)
- DCF IFS (DIFS)
- Extended IFS (EIFS)



About Packet Salvage

- Packet salvaging at network layer
  - "Packet salvaging" in DSR
  - "Local repair" in AODV

Salvaging might be less efficient

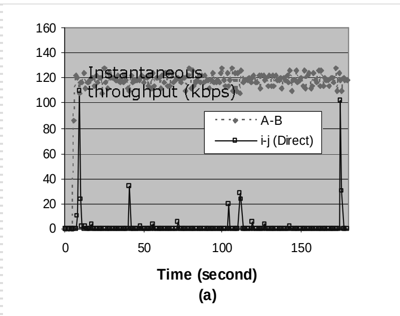
- Packet salvaging at MAC layer
  - Extremely Opportunistic Routing (ExOR)
  - Implicit Geographic Forwarding (IGF)

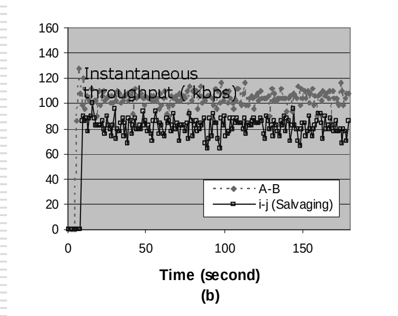
Use either link-state flooding or location information

- MASA is a MAC layer solution with less overhead

Simulation Results with TCP Traffic

(a) Direct scenario **(b) Salvaging scenario**





Duplicate Packet Filtering

- If more than one node salvages the same DATA packet, how to suppress the duplicates?
- Exploit the existing "packet filtering mechanism" in 802.11 standard

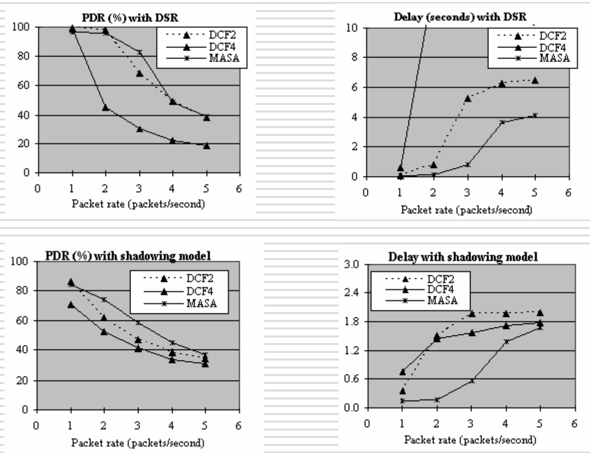
DATA packet

FC	DI	**Addr1 (receiver)**	**Addr2 (sender)**	Addr3	SC	Addr4	Data	CRC

SDATA packet

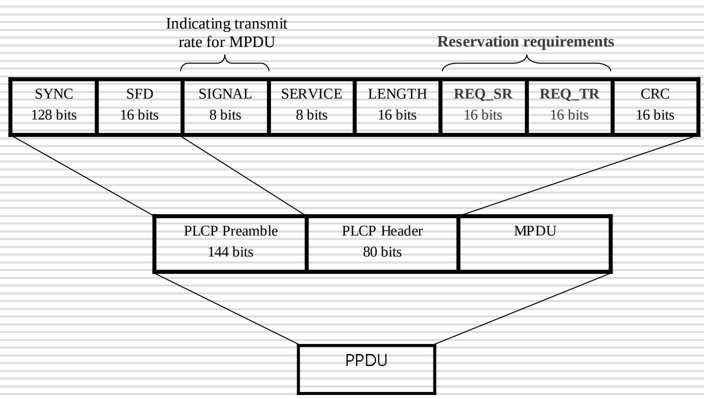
FC	DI	**Addr1 (receiver)**	**Addr2 (salvager)**	Addr3	**SC**	**Addr4 (org sender)**	Data	CRC

Simulation Results with DSR and Shadowing Propagation Model



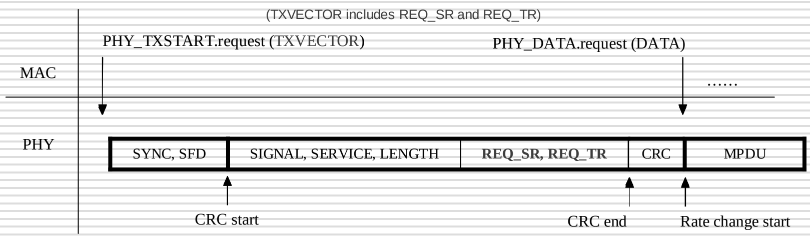
Implementation of CAD

- PLCP frame format



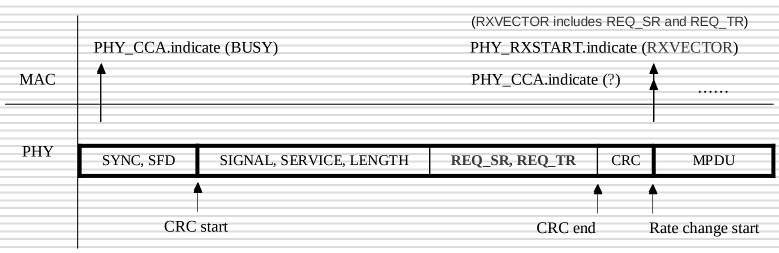
Implementation of CAD (cont.)

- Prepare and distribute reservation requirements
  - Estimate REQ_SR and REQ_TR at MAC layer
  - REQ_SR and REQ_TR are added in the TXVECTOR and passed to the PHY layer along with PHY_TXSTART.request



Implementation of CAD (cont.)

- Receive and Handle Reservation Requirements



  - If (RSSI < REQ_SR and RSSI < REQ_SR$_0$) PHY_CCA.indicate (IDLE)
  - Otherwise, PHY_CCA.indicate (BUSY), and NAV is updated according to REQ_TR

Simulation Results (Cont'd)

☐ MAC Overhead Analysis