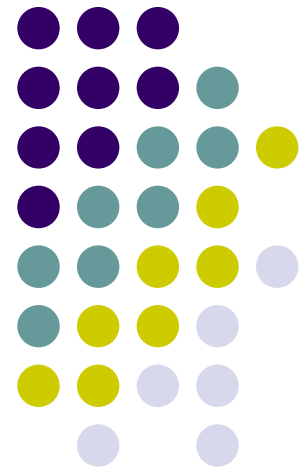


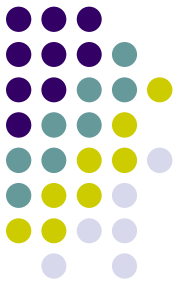
# Joint Routing and Scheduling in Wireless Mesh Networks

Leonardo Badia

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Lucca, Italy

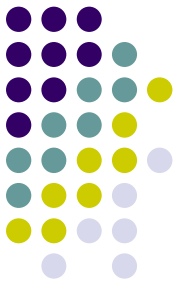
*[l.badia@imtlucca.it](mailto:l.badia@imtlucca.it)*





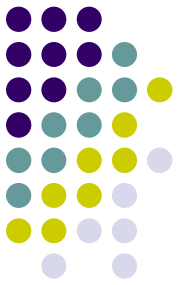
# Acknowledgements

- Alessio Botta (PhD student at IMT Lucca)
- Alessandro Erta (PhD student at IMT Lucca)



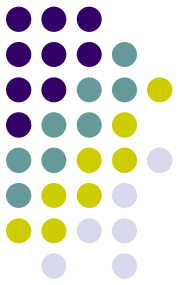
# Checklist

- Ad Hoc Networks
- Sensor Networks
- Routing Algorithms
- CSMA / CA
- Network Interference Model
- Game Theory
- Network Coding
- Genetic Algorithms



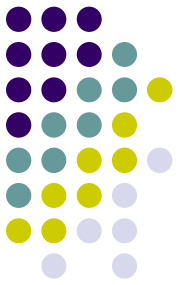
# Outline

- Wireless Mesh (Multi-hop) Networks
- Issues in Wireless Mesh Networks
  - Scheduling
  - Routing
  - Cross-layer JRS
    - Interference models
    - JRS through Genetic Algorithms
- Future Extensions



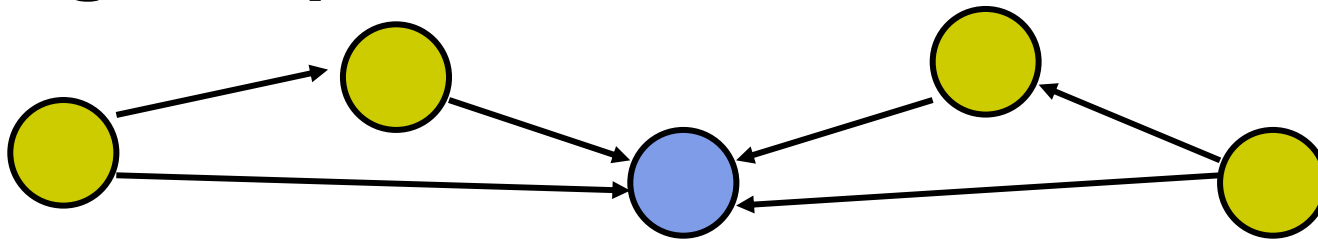
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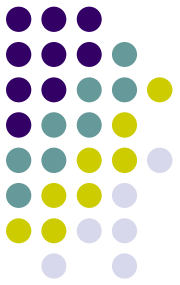


# Multi-hop networks

- Wireless technology is nowadays everywhere: cellular phones, wireless LANs...
- However, these technologies employ **single-hop** communication.

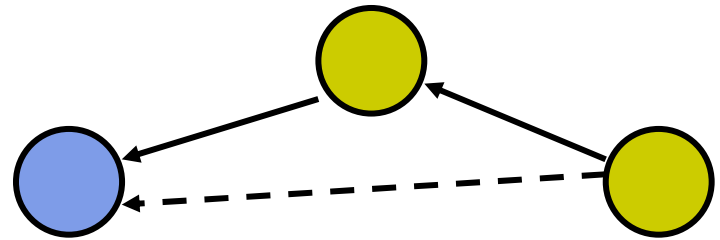


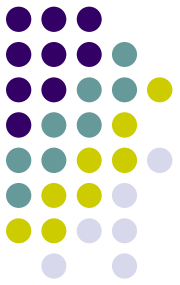
- Most of the current research effort in the wireless network community is devoted to investigate **multi-hop** network.



# Why multi-hop?

- Shorter hops (higher gain) are:
  - More reliable
  - Less power consuming
- Utilizing relay nodes:
  - Improves the failure tolerance
  - Alleviate the computational power required at the center of the network
  - Enables **networking** even without a fixed **network infrastructure** (both technical and theoretical consequences).



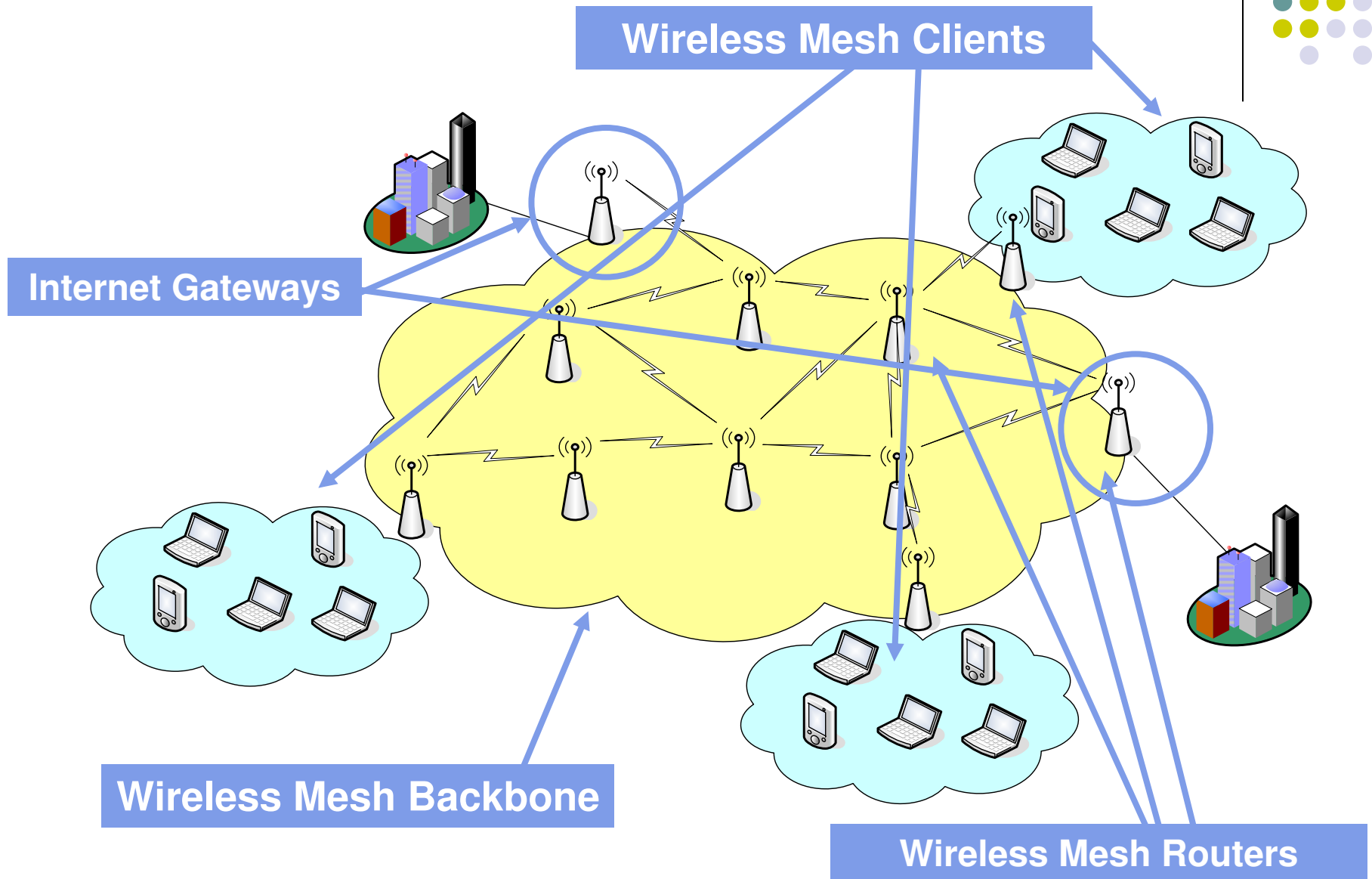
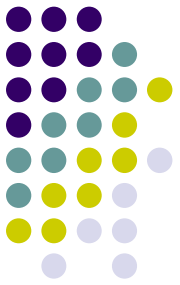


# Wireless Mesh Networks (WMN)

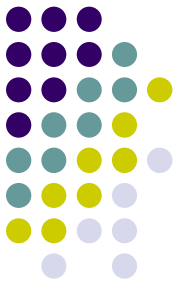
- A promising technology paradigm for broadband Internet access
- In a WMN, mobile clients are connected to **wireless access routers** similarly to MT→AP in a WLAN, but access routers are connected through wireless links.
- Some of the access routers are wired to the Internet and serve as gateways.



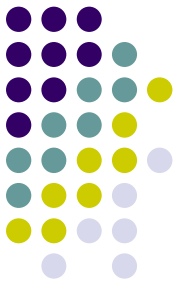
# WMN Architecture



# Wireless Mesh Networks (WMN)

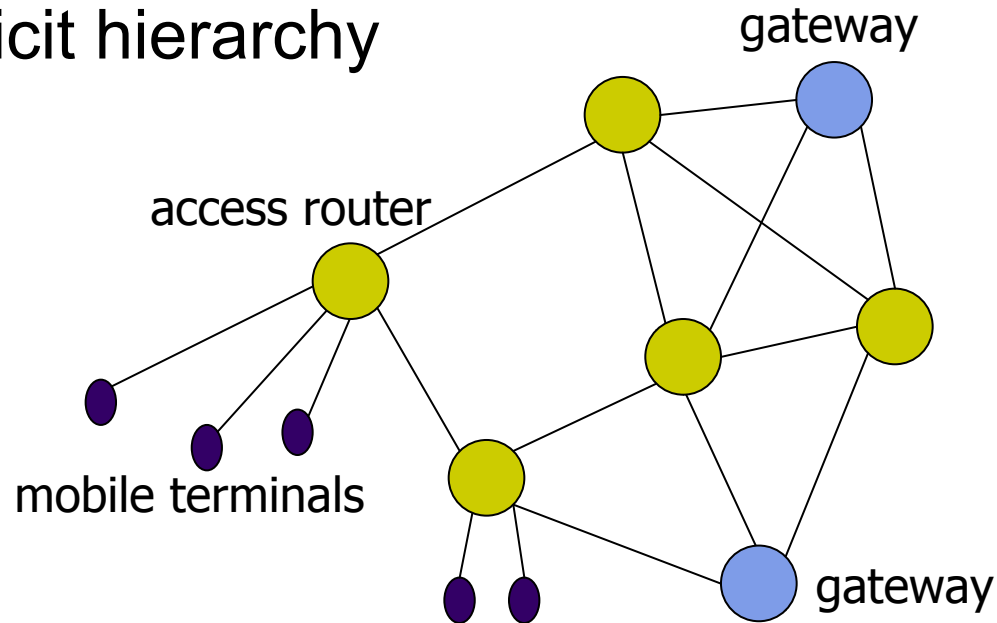


- ↑ Easy to manage
- ↑ Increased coverage by placing more routers.
- ↑ Can extend coverage for rural areas.
- ↑ Can extend coverage for dense urban areas.
- ↑ **Fixed** routers can be placed near to a power outlet (so energy is not an issue).

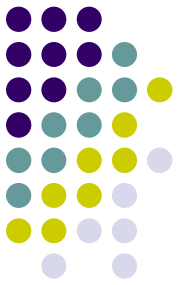


# Wireless Mesh Networks (WMN)

- Implicit hierarchy

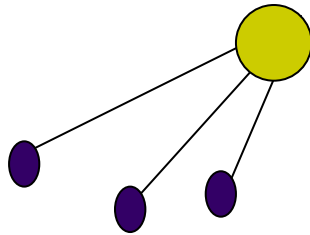


- The access from a terminal to a router and then through the backbone towards the gateway employs multi-hop

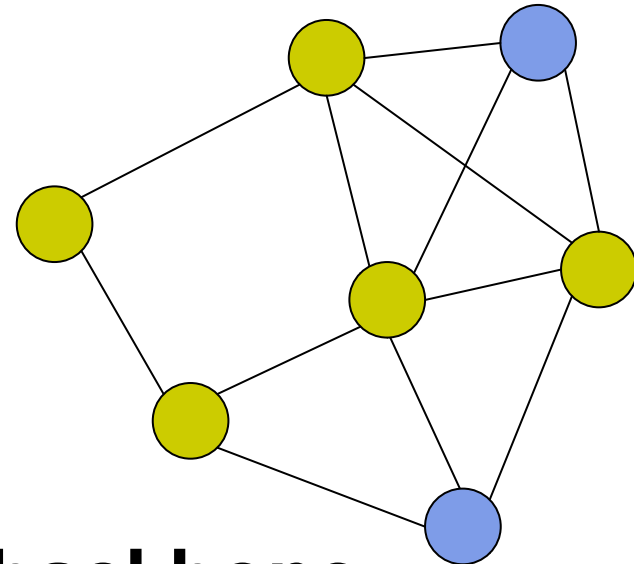


# Wireless Mesh Networks (WMN)

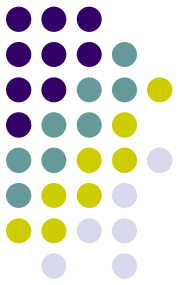
- WMN management can be decoupled into:



- **MT → AR part:**  
similar to classic  
management of  
cellular networks  
or Wireless LANs



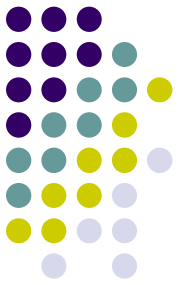
- **backbone:**  
uses solutions typical of  
multi-hop Networks



# Wireless Mesh Networks (WMN)

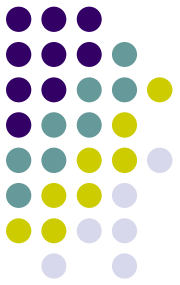
- Actually, most of the solutions proposed for WMN are directly taken from Ad Hoc and Sensor networks.
- Advantages of WMN vs. Ad Hoc:
  - Nodes are not mobile
  - Nodes are often attached to a power outlet
- Advantages of WMN vs. Sensors:
  - Nodes are not tiny terminals and can perform computations and information processing

# Wireless Mesh Networks (WMN)



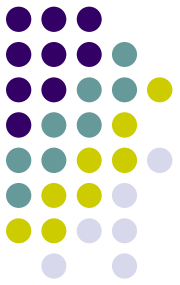
- Known problems of WMNs:
  - They need to rely on existing protocols (e.g., IEEE 802.11) not designed for multi-hop;
  - Multihop very unlikely works for more than 3 hops
- Performance are limited by

**WIRELESS  
INTERFERENCE**



# Outline

- Wireless Mesh (Multi-hop) Networks
- Issues in Wireless Mesh Networks
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  - Routing
  - Cross-layer JRS
    - Interference models
    - JRS through Genetic Algorithms
- Future Extensions

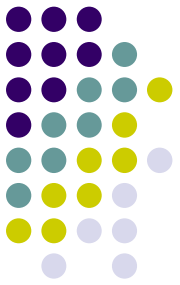


# Scheduling for WMN

- Random MAC (e.g., CSMA / CA)
- Scheduled (TDMA) MAC
- Known problems of multi-hop scheduling:
  - Hidden terminal problem
  - Exposed terminal problem
  - More in general:

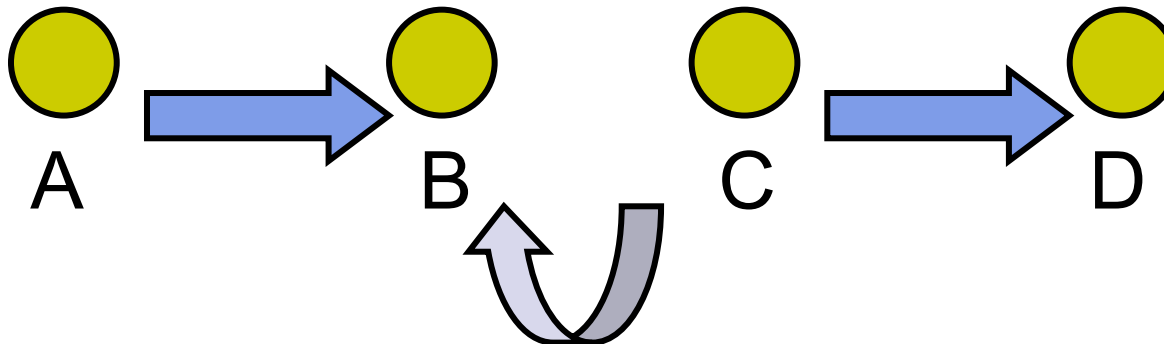
**WIRELESS  
INTERFERENCE**



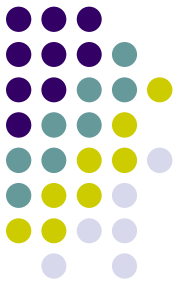


# Hidden terminal problem

- Transmissions:  $A \rightarrow B$ ,  $C \rightarrow D$ .
- Assume all neighbors hear each other.
- Nodes A and C are “hidden” to each other.

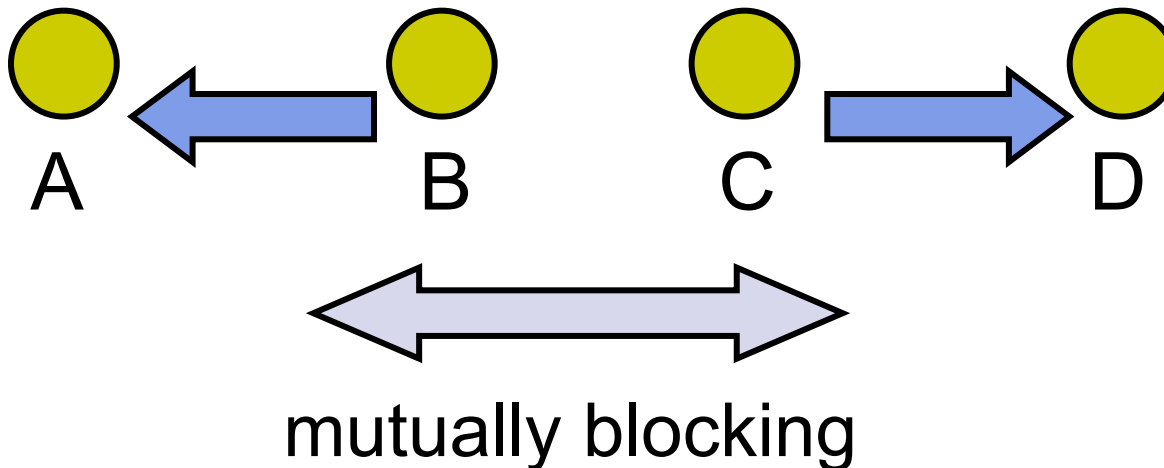


causes collision

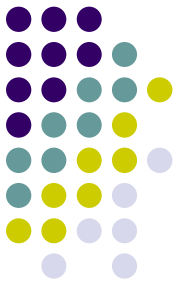


# Exposed terminal problem

- Transmissions:  $B \rightarrow A$ ,  $C \rightarrow D$ .
- Assume a solution to the hidden terminal problem is used.
- Nodes B and C are “exposed” to each other.



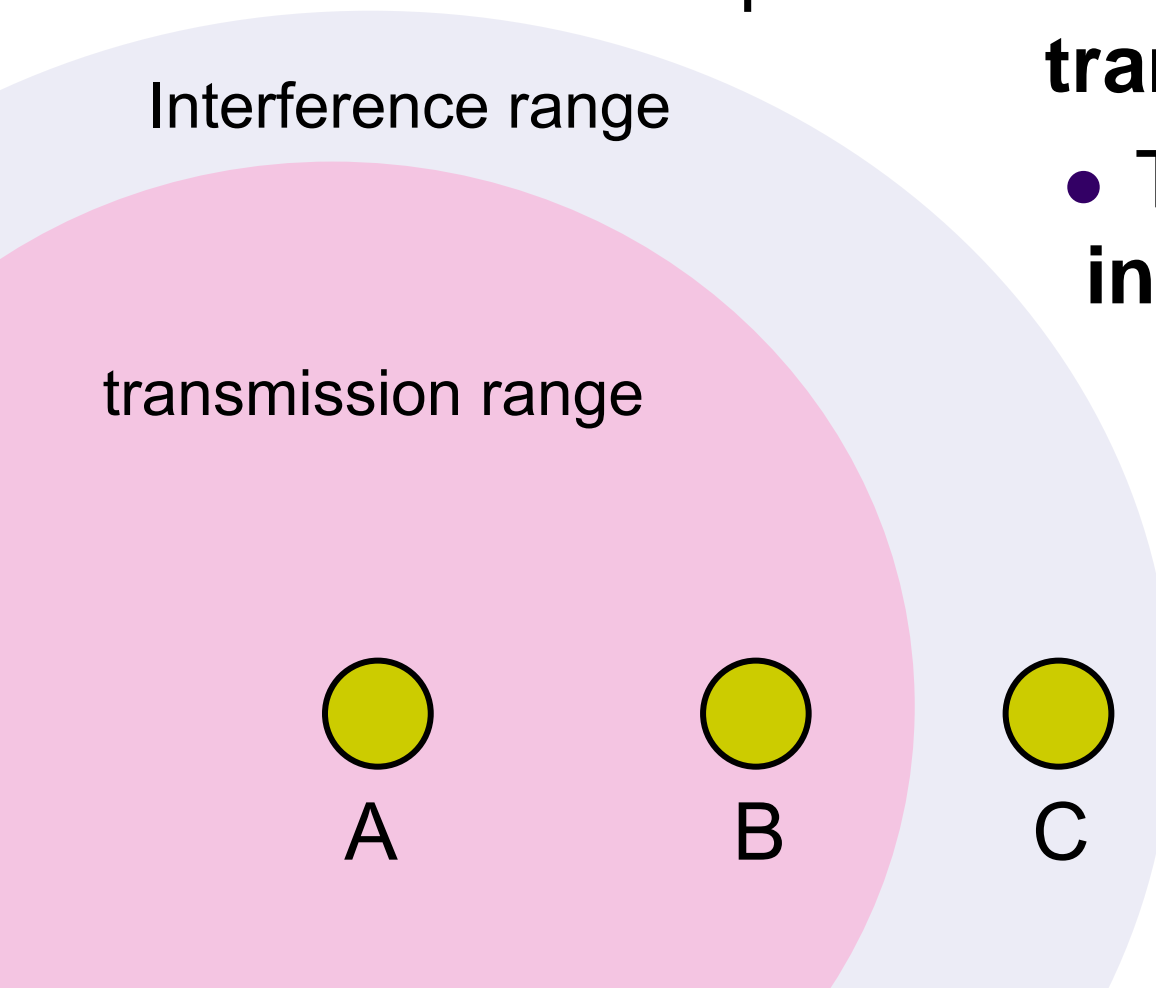
# Propagation and wireless ranges

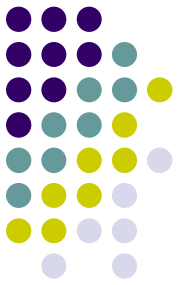


- Simplification: we have a constant **transmission range**.

- This is in general  $\neq$  **interference range**.

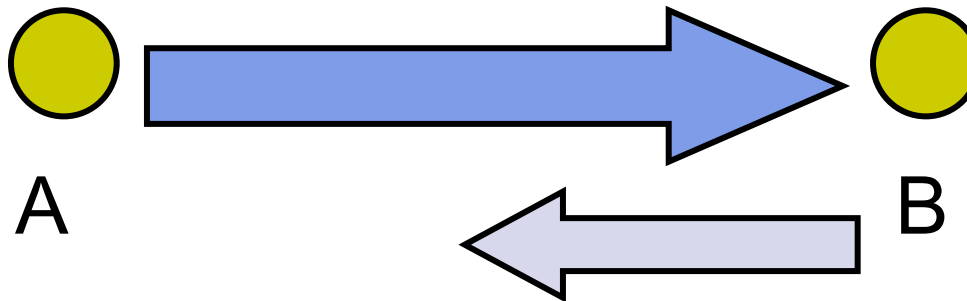
- A node may not hear all the interferers.

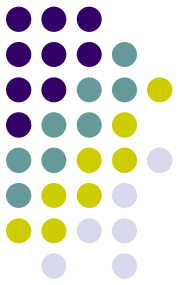




# Transmission asymmetry

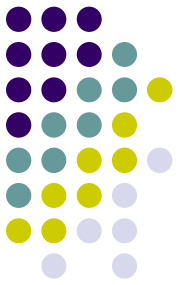
- The assumption “If I can hear you, you can hear me” is generally FALSE (often due to the use of different power levels).
- Further deafness problem due to transmission asymmetry.





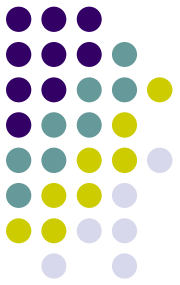
# CSMA scheduling: Pros&Cons

- ↑ easy to implement.
- ↑ already everywhere.
- ↓ considers the collision-model as perfect (neglects capture effect or more sophisticated interference aspects)
- ↓ it is sender-centric, whereas interference is a receiver-centric phenomenon
- ↓ deafness and asymmetry are not solved



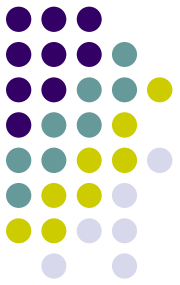
# TDMA scheduling: Pros&Cons

- ↑ potentially collision-free and interference-free
- ↓ requires a centralized controller
- ↓ requires network-wise knowledge
- ↓ requires an accurate interference model
- possible future extension: design of an efficient distributed TDMA MAC



# Outline

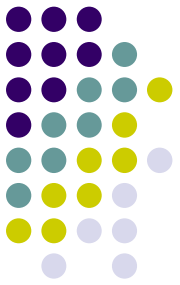
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# Routing in WMNs

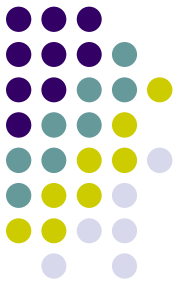
- Typical solutions of Ad Hoc Networks
  - DSR, AODV, DSDV
- Typical solutions of Sensor Networks
  - Flooding, Geographic Routing
- Traffic-aware routing
  - Routing metrics which account for wireless link quality, failure rate, delay, QoS
- Possible extensions: Multipath Routing, Cooperation, Network Coding





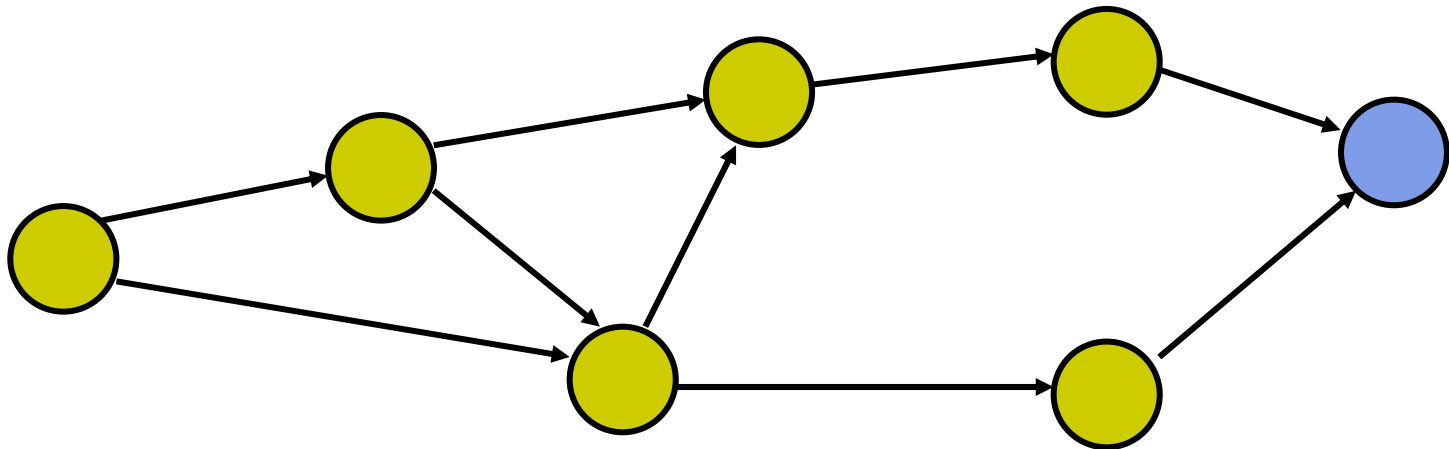
# Some criticisms

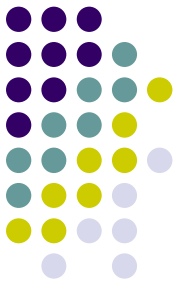
- Mesh Routers are usually not mobile.
  - Thus, proactive strategies can be used.
- Sometimes, so-called Topology Control is used to manage network connectivity.
- From the point of view of routing it is better **not to limit** the number of alternatives.
- Beware of interference-aware (i.e., selecting interference free routes) solutions!



# Multi-path routing

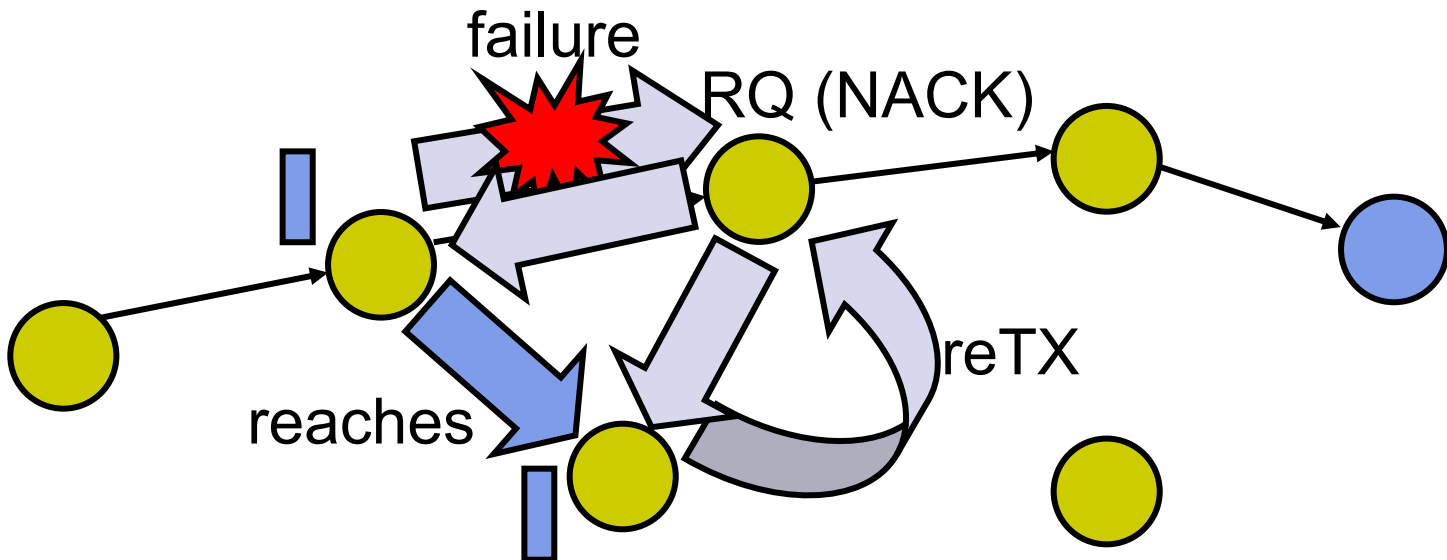
- A single source-destination flow is associated with multiple routes.
- Needs to specify a mechanism for the choice.
- Trade-off between efficiency and routing overhead.

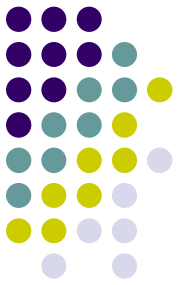




# Cooperation

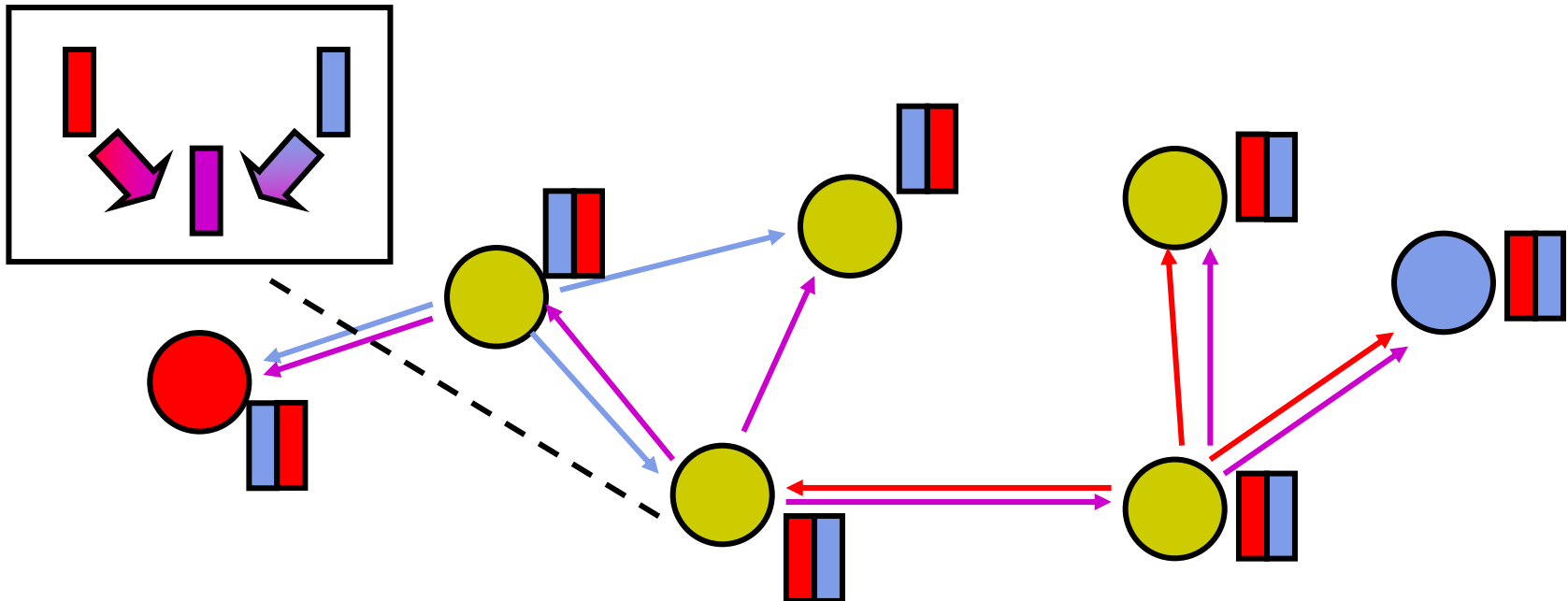
- Exploits multipath especially in case of **failure**.
- A node who is not on the originary route can re-transmit a packet for which a NACK is detected.

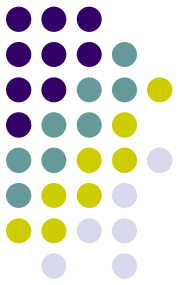




# Network coding

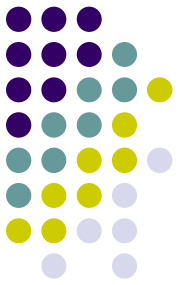
- Codifies the packet to send (think of a XOR)
- Packets are re-combined at the receiver's side
- Decreases #TX → Improves efficiency





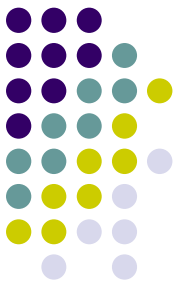
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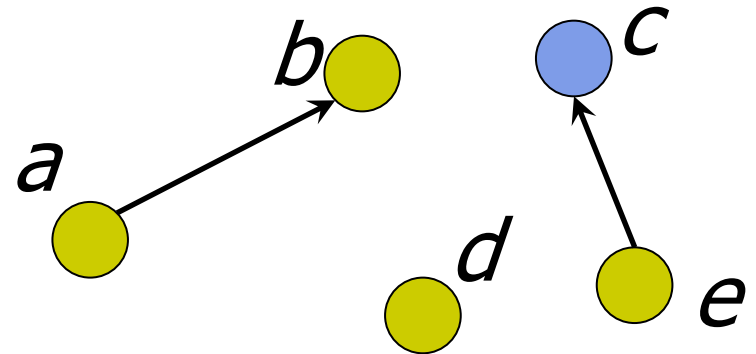
# Cross-Layering at Layer 2.5

- A general observation
  - The efficiency of the scheduler depends on the efficiency of the routing protocol
  - A “good” scheduling strategy can achieve very bad performance if the routes are not optimized.
- Thus, one might think of addressing routing and scheduling **jointly**.



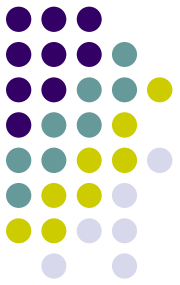
# Model for JRS in WMNs

- The WMN backhaul is represented as a graph  $\mathcal{G} = (\mathcal{N}, \mathcal{E})$  (i.e., vertices, edges).
- Any element of  $\mathcal{E}$  is  $(i, j): i, j \in \mathcal{N}$   
(links are **directional**)
- Variables  $x_{ij}(t)$  in  $\{0, 1\}$  represent the activation of  $(i, j) \in \mathcal{E}$  at time  $t \in 0, 1, \dots, T-1$



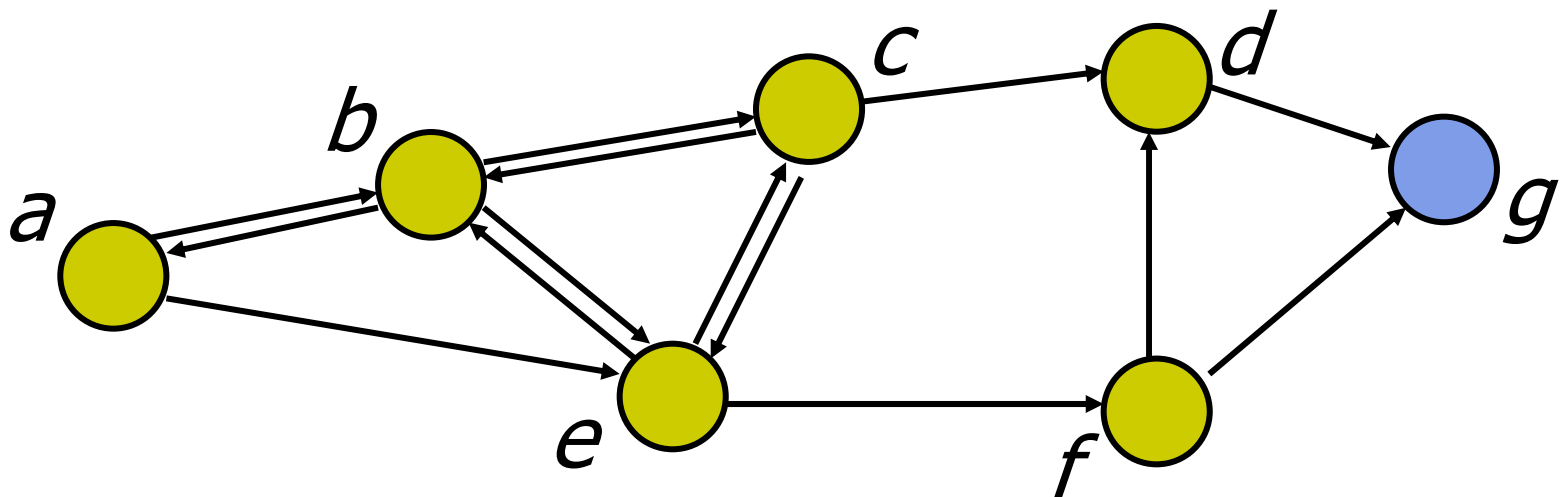
At time  $t$  links  $a \rightarrow b$  and  $e \rightarrow c$  are active

$$x_{ab}(t) = x_{ec}(t) = 1$$

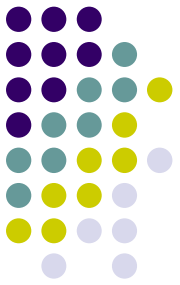


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- An element of  $\mathcal{E}$  is  $(i, j): i, j \in \mathcal{N}$  ;  
links are **directional**, so  $(i, j) \neq (j, i)$

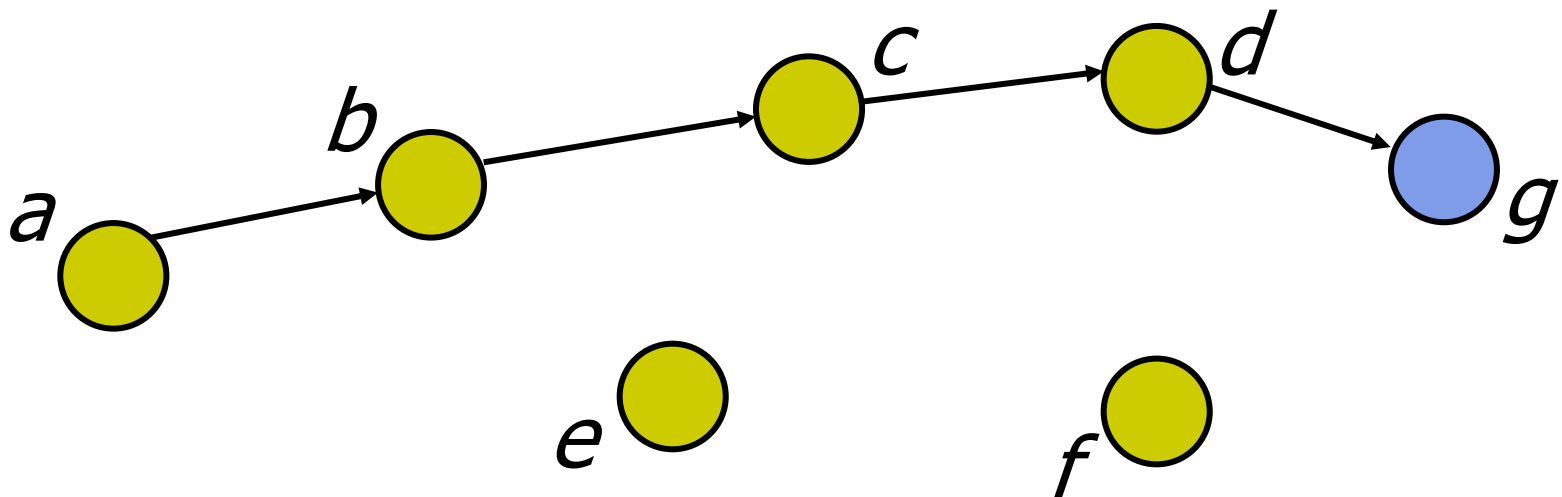


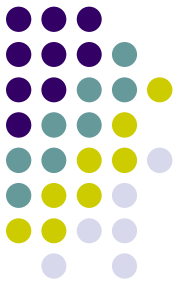




# Model for JRS in WMNs

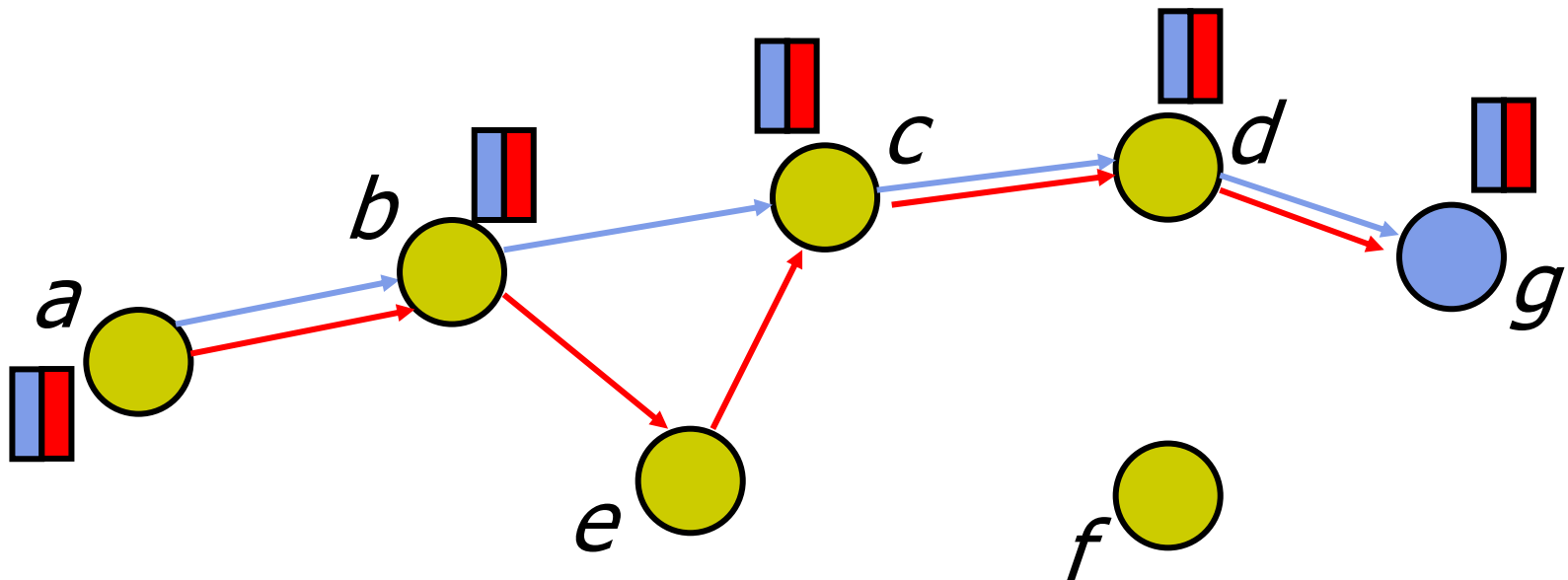
- Routes are derived from the link activation pattern over time (layering is broken).
  - Routes depend on packets and vice versa (may need a re-ordering algorithm).

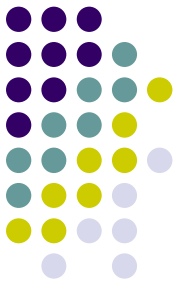




# Model for JRS in WMNs

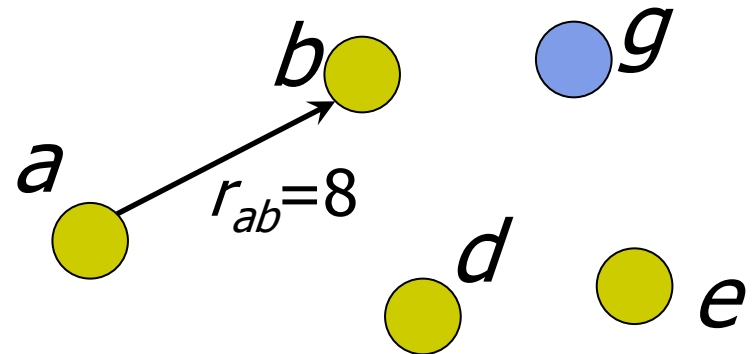
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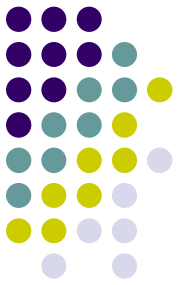
# JRS in WMNs

- Data flows are represented by variables  $q_i(t)$  (queue length at  $i$ ) varying over time.
- Any element of  $\mathcal{E}$  is associated with a rate (link capacity)  $r_{ij} \geq 0$
- Data flows evolve over time and are to be delivered to the gateways.



At time  $t$ :  $q_a(t)=10$   
 $q_b(t)=1$

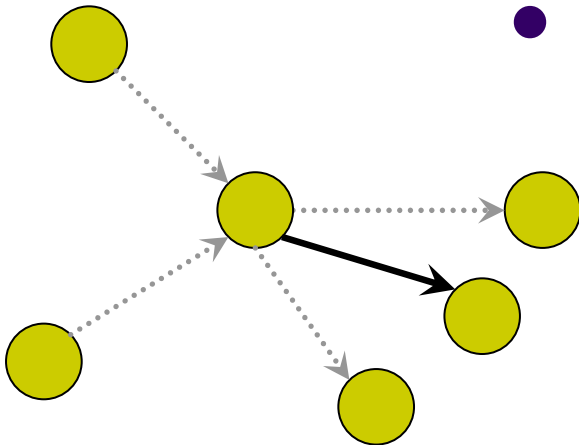
At time  $t+1$ :  $q_a(t+1)=2$   
 $q_b(t+1)=9$



# JRS in WMNs: constraints

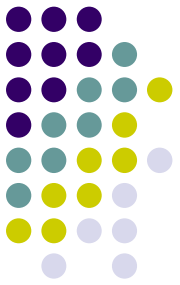
- The activation of links on the graph is subject to constraints.
- **Primary compatibility constraints:**

- A node can transmit AND receive on one active link only.

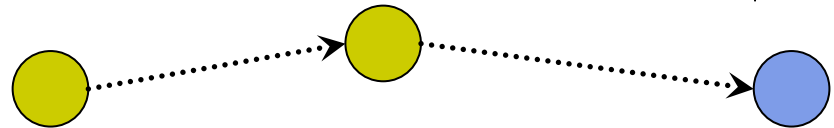


$$\sum_{j \in \mathcal{R}_i} x_{ij}(t) + \sum_{j \in \mathcal{S}_i} x_{ji}(t) \leq 1 \quad \forall i \in \mathcal{N}, \forall t$$

# JRS in WMNs: constraints



- **Flow constraints:**

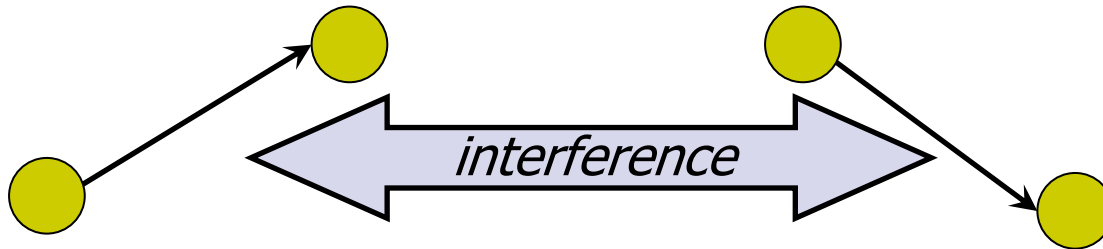


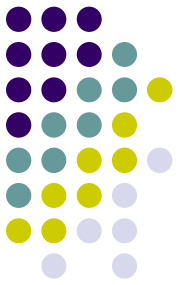
At time  $T$  all the flows have been delivered.

$$\sum_{i \in \mathcal{N}} q_i(0) = \sum_{i \in \mathcal{Y}} q_i(T) \quad \mathcal{Y} = \text{set of gateways}$$

- **Interference compatibility constraint:**

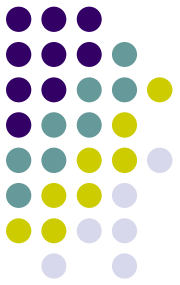
A node transmit only if wireless interference does not disturb the transmission.





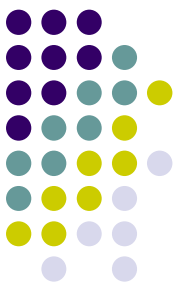
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# Interference constraints

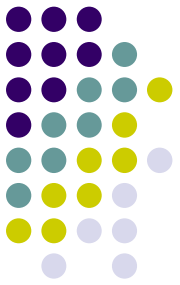
- Though the graph model is nice, modeling interference depends on physical aspects.
- **Wireless interference constraints** should not be confused with the **primary compatibility constraints**.
- In primary compatibility constraints, incompatible links **share a node**.
- Interference constraints involve at least 4 different nodes (2 transmitters, 2 receivers).



# Characterizing interference

- Several approaches exist in the literature to address this problem.
- However, some terminology **ambiguity** is present in the literature as regards to the definition models to characterize interference.
- Our goal is:
  - Resolve the terminology ambiguity.
  - Discuss the **choice** of the interference model that better fits our design needs.

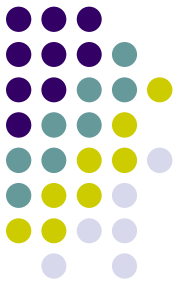




# Characterizing interference

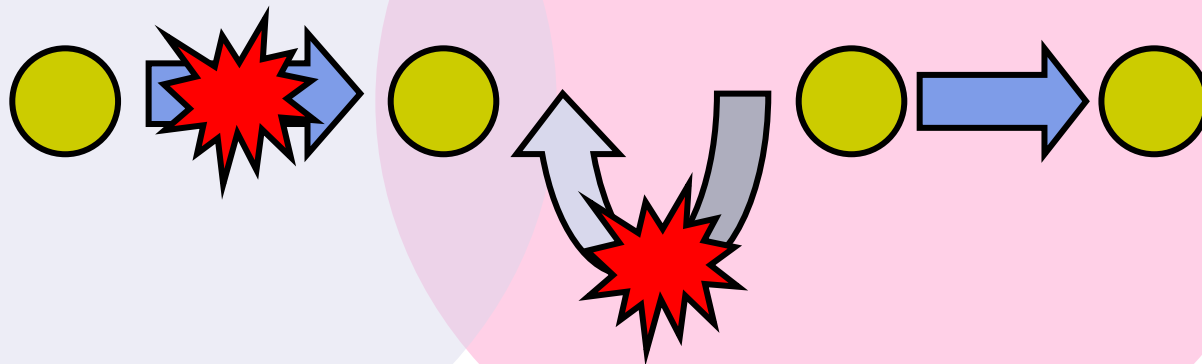
- Interference compatibility: it depends on the abstraction made to characterize interference and varies depending on the model.
  - Protocol interference models
  - Physical interference model

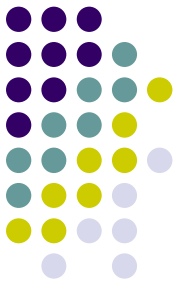
Note we say “models”



# Protocol interference models

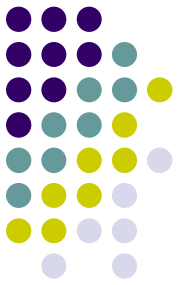
- Use a **geometric abstraction** of the network.
- Easy to use and understand.
- Model interference through collisions.





# Who causes interference?

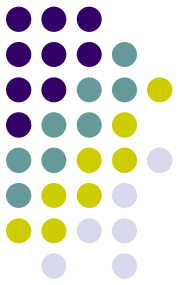
- There are different assumptions on who causes interference, and to whom.
- IEEE 802.11 requires symmetric links (for handshake exchange) → A logical transmitter also acts as a receiver, and vice versa.
- Other kinds of MAC (e.g., IEEE 802.16, centralized TDMA) do not have this problem.



# Protocol models: examples

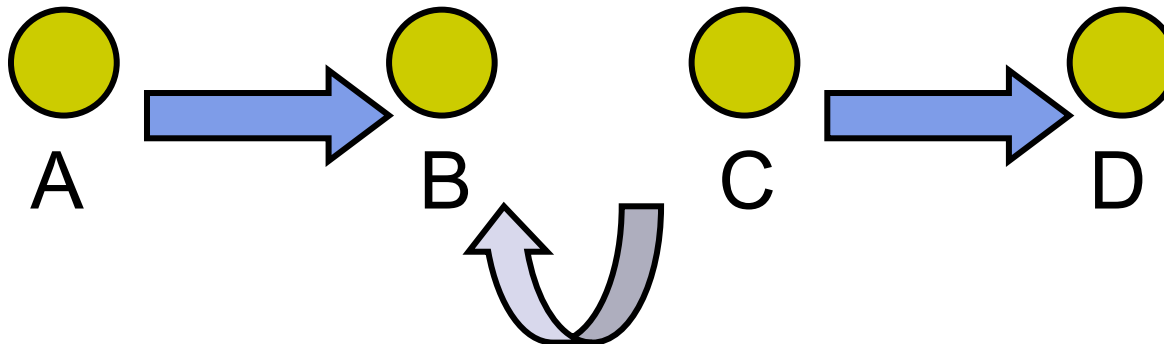
<i>01</i> protocol model	<b>At most one link</b> can be active at a time. Interference among links is prevented a priori.
<i>11</i> protocol model	Nodes in the coverage area of both <b>transmitter</b> and <b>receiver</b> must not <b>transmit</b> nor <b>receive</b> .
<i>16</i> protocol model	Nodes in the coverage area of the <b>receiver</b> must not <b>transmit</b> .

The primary compatibility is always implicitly satisfied.

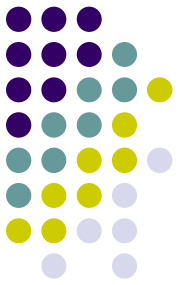


# Hidden terminal problem

- Transmissions:  $A \rightarrow B$ ,  $C \rightarrow D$ .
- Solved by all protocol models.
- Only one transmission can be active.

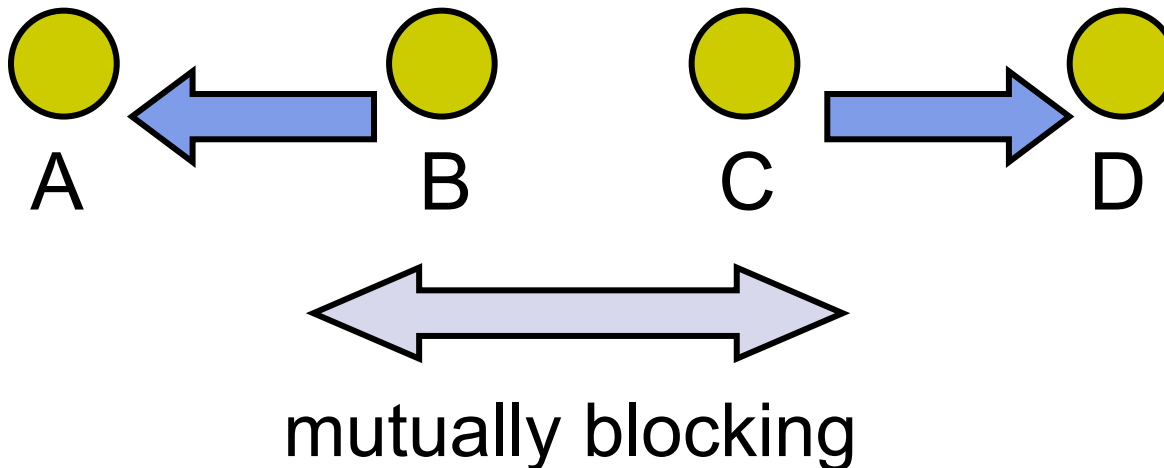


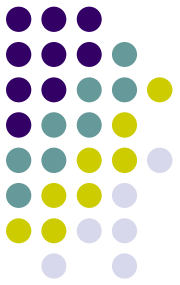
causes collision



# Exposed terminal problem

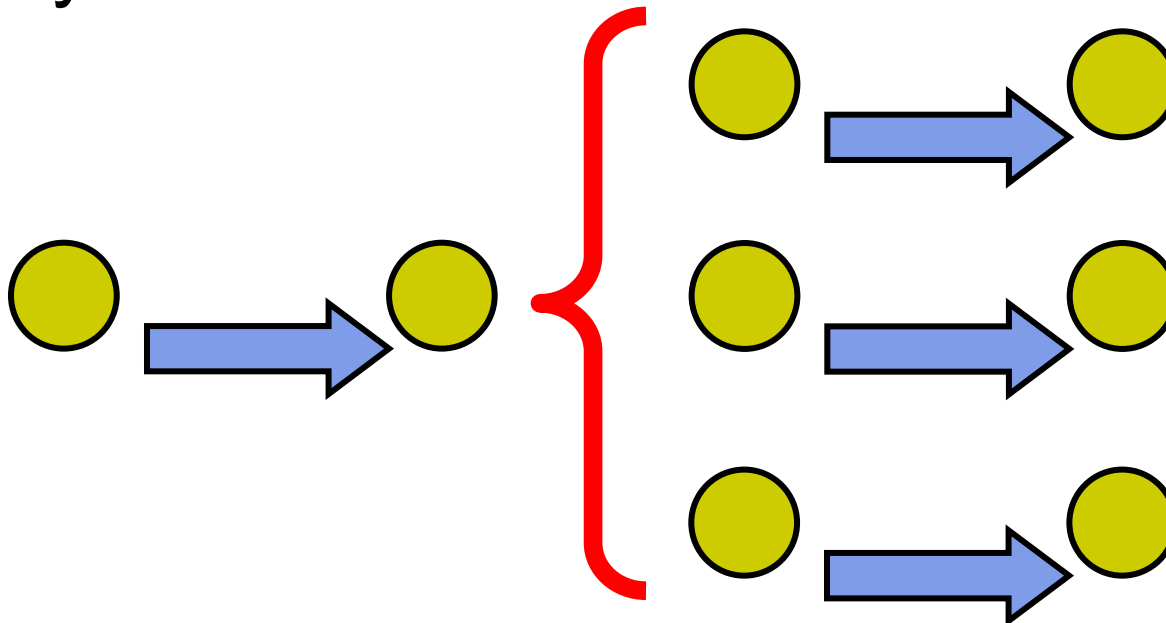
- Wanted transmissions:  $B \rightarrow A$ ,  $C \rightarrow D$ .
- Not solved by 01protocol and 11protocol models.
- Solved by 16protocol model.

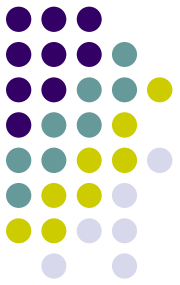




# Other cons of protocol models

- The protocol models characterize interference as a **binary relationship**.
- However, interference is cumulative and not binary.





# Physical interference model

- Better takes into account physical reality.
- Requires to know the path gain on all edges.
- Allows to account for propagation effects (e.g., fading).

$$SIR = \frac{g_{ij} P_i}{\sum_{k \neq i \text{ active TX}} g_{kj} P_k} \geq \gamma$$

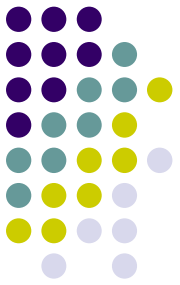
Useful received power

Received interference

hard part!

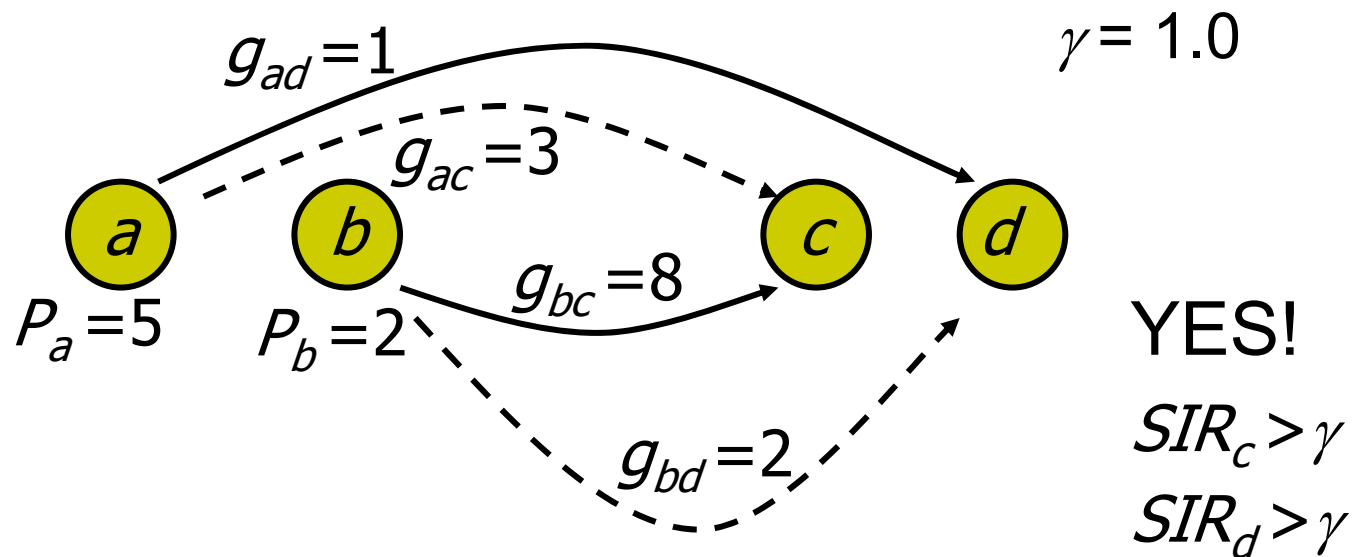
Required Threshold





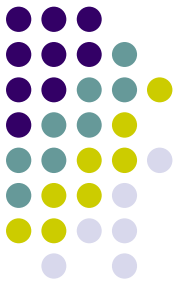
# Physical interference model

- The physical interference model is complicated but takes into account also counter-intuitive effects.

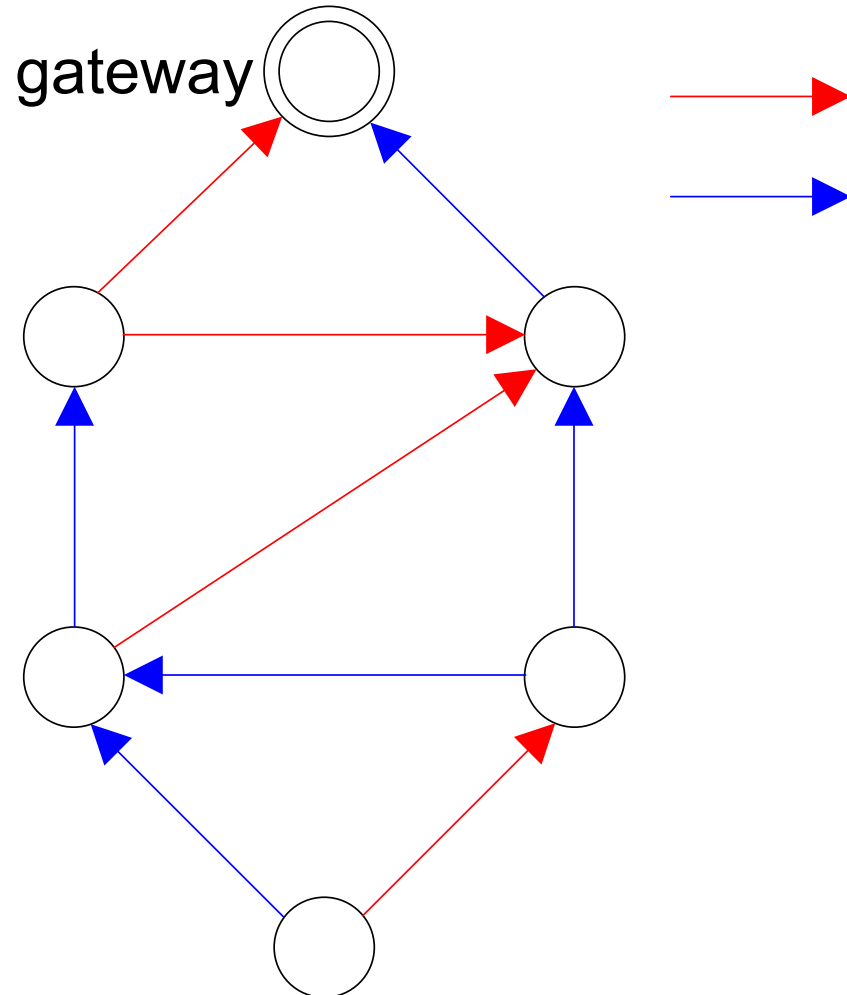


Is this allocation feasible?

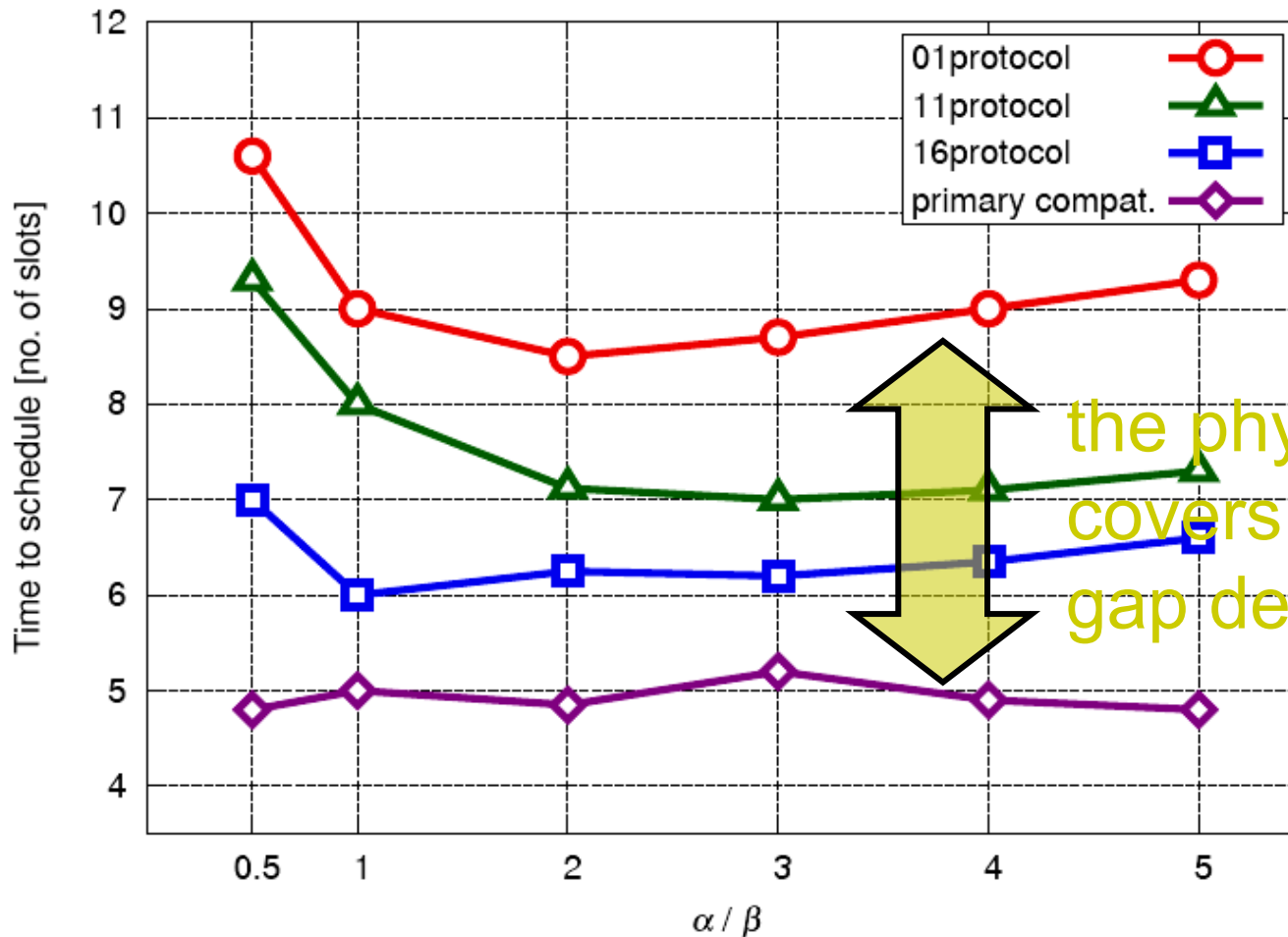
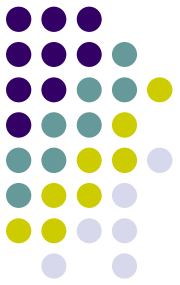
# Comparison of models



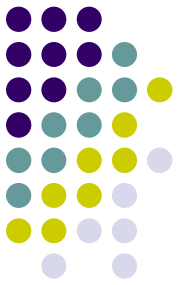
- Network topology



# Comparison of models

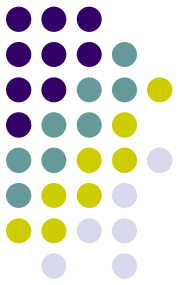


the physical model  
covers the whole  
gap depending on  $\gamma$



# Outline

- Wireless Mesh (Multi-hop) Networks
- Issues in Wireless Mesh Networks
  - Scheduling
  - Routing
  - Cross-layer JRS
    - Interference models
    - JRS through Genetic Algorithms
- Future Extensions

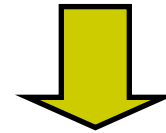


# Back to JRS...

- For these reasons, we apply the so-called **physical-interference model**.
- Importantly, it needs artifices to keep the optimization problem linear.

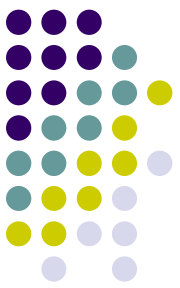
*direct formulation*

$$\gamma x_{ij}(t) \leq \frac{g_{ij} x_{ij}(t)}{\sum_{k \in \mathcal{S}_j \setminus \{i\}} g_{kj} \sum_{\ell \in \mathcal{R}_k \setminus \{j\}} x_{k\ell}(t)} \quad \forall (i, j) \in \mathcal{E}, \forall t$$



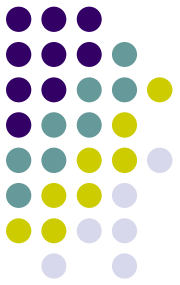
$$g_{ij} \geq \gamma \sum_{k \in \mathcal{S}_j \setminus \{i\}} g_{kj} \left( \left( \sum_{\ell \in \mathcal{R}_k \setminus \{j\}} x_{k\ell}(t) \right) + x_{ij}(t) - 1 \right) \quad \forall (i, j) \in \mathcal{E}, \forall t$$

*equivalent linear version*



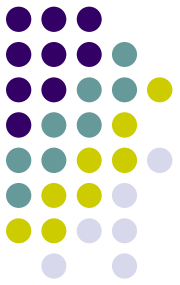
# Fluidic schedule

- In many approaches, the link activations variable are averaged over time.
- This result in a fluidic formulation, where link activation is no longer an integer binary variable, but a real value in  $[0,1]$ .
- Other constraints are relaxed accordingly.
  - This relaxation may be arguable from the physical point of view...



# Fluidic schedule

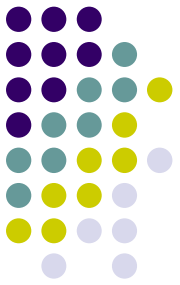
- The fluidic schedule can be useful to derive **capacity bounds**. When a link is utilized at 100%, the capacity of the network is surely reached (upper bound only).
- More in general, there are other approximation issues in the fluidic schedule.
- To translate it in practical solutions (i.e., the **actual pattern** of link activation over time) is still an open problem.



# Outline

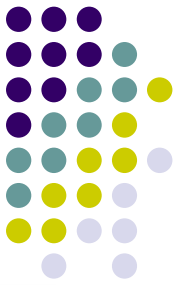
- Wireless Mesh (Multi-hop) Networks
- Issues in Wireless Mesh Networks
  - Scheduling
  - Routing
  - Cross-layer JRS
    - Interference models
    - JRS through Genetic Algorithms
- Future Extensions





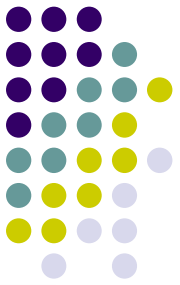
# Genetic Algorithms

- A meta-heuristic technique for optimization
- They mimic natural selection and evolution mechanism
- Are appealing because:
  - Highly customizable
  - Handle both discrete - continuous problems easily
  - Scale reasonably by adjusting meta-parameters
  - Can be designed to include experts' knowledge
  - Always give a solution



# A basic GA

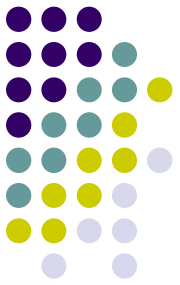
```
initialize  $P(0)$   
repeat  
    evaluate  $P(t)$  via fitness_function  
    apply selection to choose parents  
    apply crossover to generate offspring  
    apply mutation to offspring  
    generate  $P(t+1)$   
    increase  $t$  by 1  
until a termination is reached
```



# A basic GA

```
initialize  $P(0)$   
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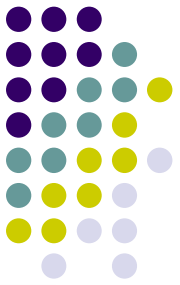
- Generate initial random individuals for the population at  $t = 0$



# A basic GA

```
initialize  $P(0)$   
repeat  
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    apply selection to choose parents  
    apply crossover to generate offspring  
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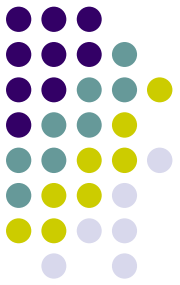
- Use a properly defined **fitness function** to evaluate the goodness of each individual in the population as a solution to the problem



# A basic GA

```
initialize  $P(0)$   
repeat  
    evaluate  $P(t)$  via fitness_function  
    apply selection to choose parents  
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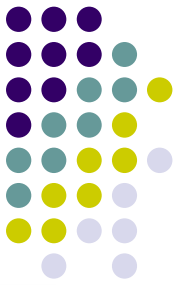
- Decide which individuals in the population are best candidates to be parents for individuals in the next population, by means of a **selection operator**



# A basic GA

```
initialize  $P(0)$   
repeat  
    evaluate  $P(t)$  via fitness_function  
    apply selection to choose parents  
    apply crossover to generate offspring  
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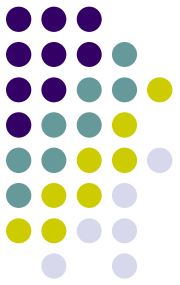
- Mate couples of parents to generate children which inherit genetic features by both parents, by means of a **crossover operator**



# A basic GA

```
initialize  $P(0)$   
repeat  
    evaluate  $P(t)$  via fitness_function  
    apply selection to choose parents  
    apply crossover to generate offspring  
    apply mutation to offspring  
    generate  $P(t+1)$   
    increase  $t$  by 1  
until a termination is reached
```

- Introduce some new and possibly previously unused genetic material in the new population, by means of a **mutation operator**

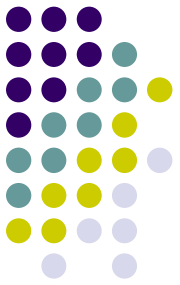


# A basic GA

```
initialize  $P(0)$   
repeat  
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    apply selection to choose parents  
    apply crossover to generate offspring  
    apply mutation to offspring  
    generate  $P(t+1)$   
    increase  $t$  by 1  
until a termination is reached
```

- Let the best parents survive and join the children in the new population via an **elitist strategy**



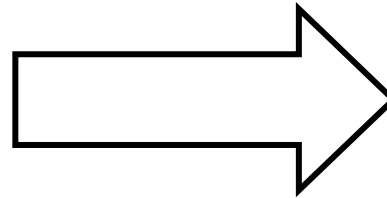
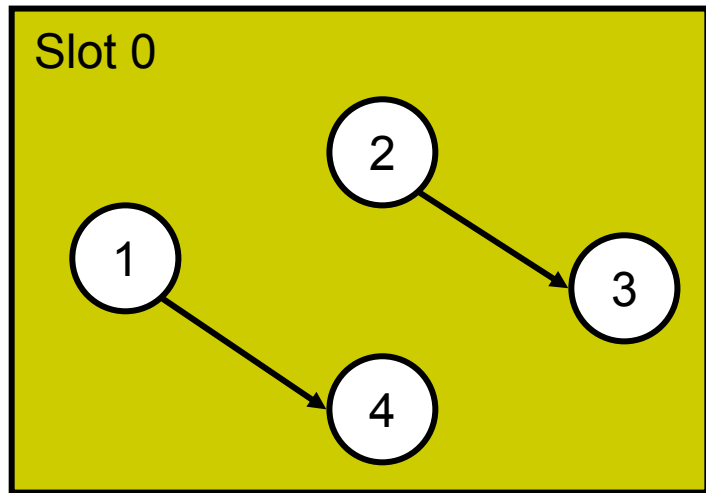
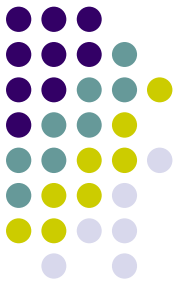


# A basic GA

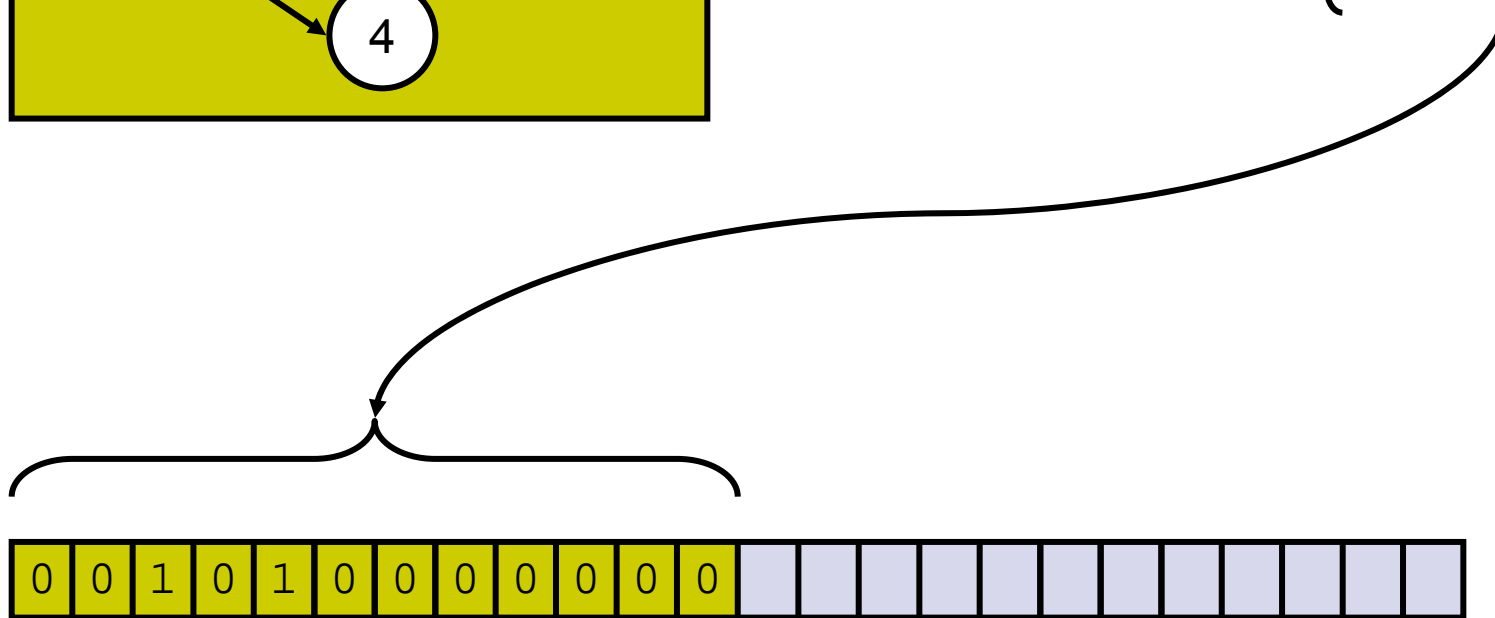
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    apply selection to choose parents  
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    apply mutation to offspring  
    generate  $P(t+1)$   
    increase  $t$  by 1  
until a termination is reached
```

- Iterate until a termination condition occurs  
(i.e., maximum number of generations reached)

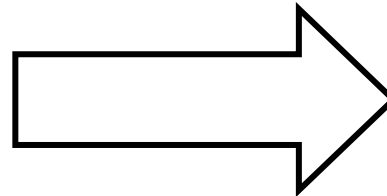
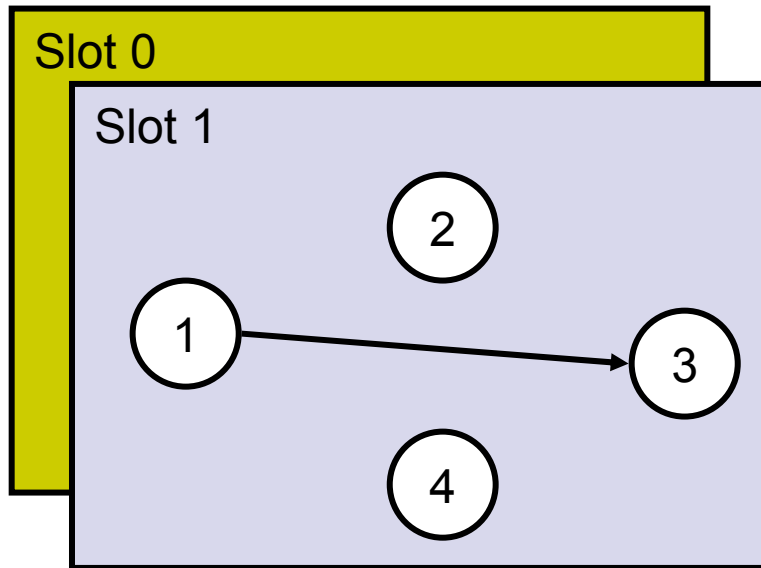
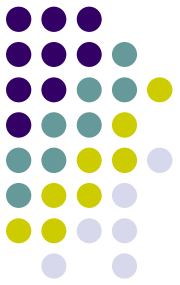
# The coding schema



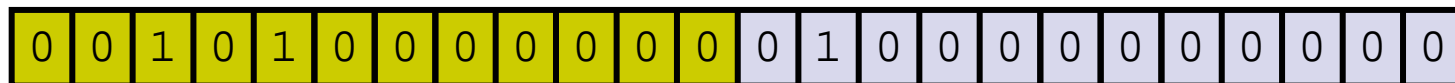
$$\begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

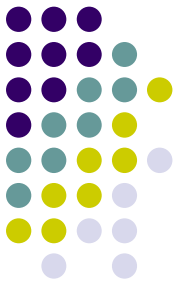


# The coding schema



$$\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

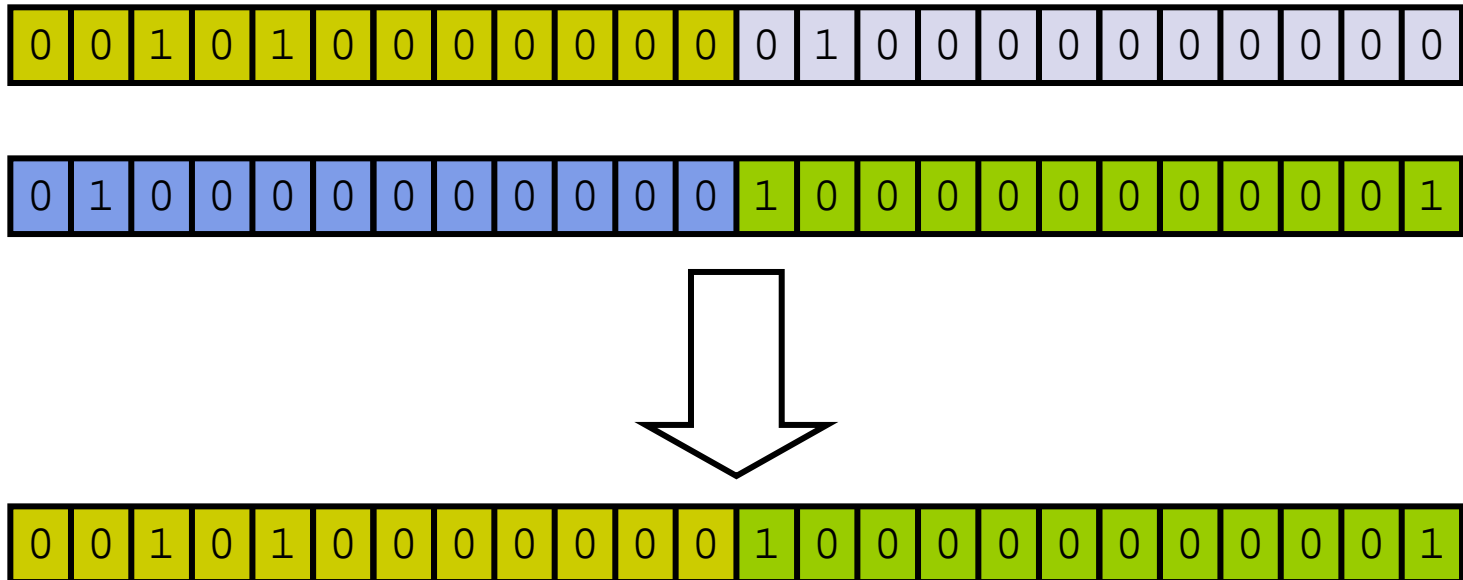




# Customized Genetic Operators

- Crossover

- Based on the 0.5 – uniform crossover
- Acts with **slot-level** or link-level granularity



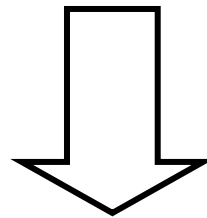
# Customized Genetic Operators



- Crossover
  - Based on the 0.5 – uniform crossover
  - Acts with slot-level or **link-level** granularity

0 0 1 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0

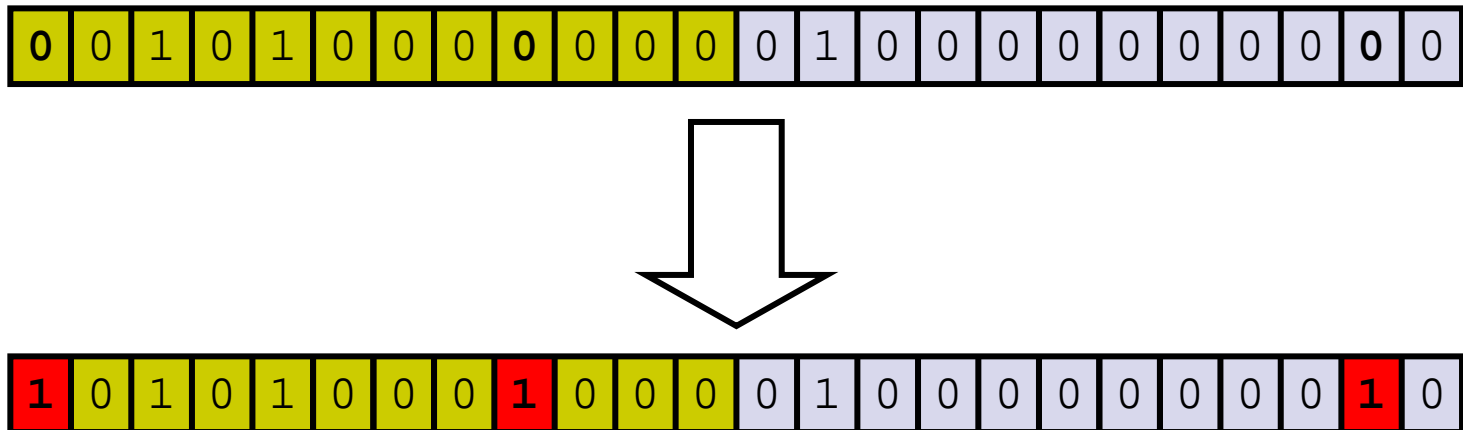
0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1



0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1

# Customized Genetic Operators

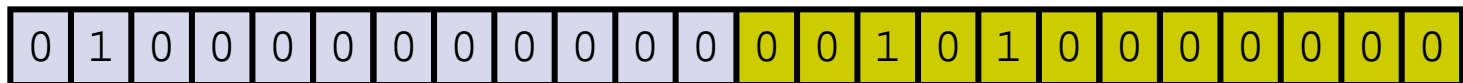
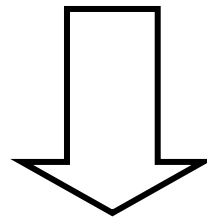
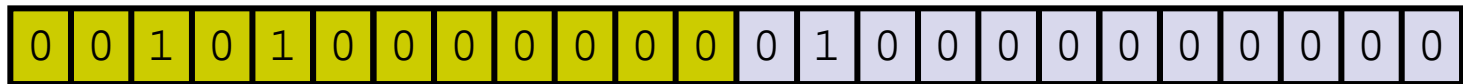
- Mutation
  - Link-level granularity:
    - Apply the uniform random mutation (bits are changed in a binary way)



# Customized Genetic Operators



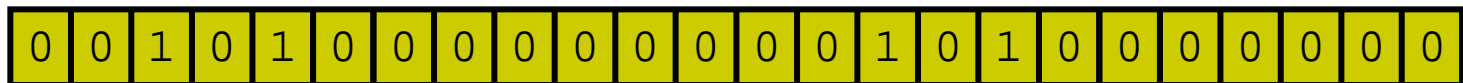
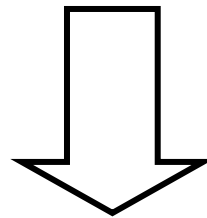
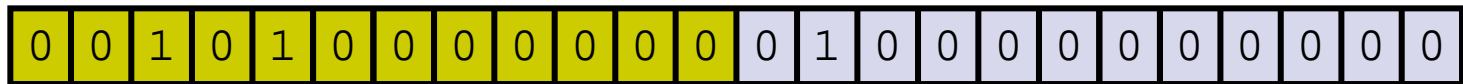
- Mutation
  - Slot-level granularity
    - **Scramble some of the time slots**
    - Replace some time slots with a copy of other ones
    - Replace some time slots with empty slots



# Customized Genetic Operators

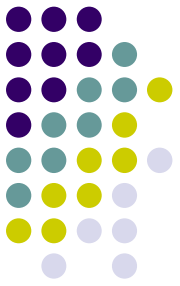


- Mutation
  - Slot-level granularity
    - Scramble some of the time slots
    - **Replace some time slots with a copy of other ones**
    - Replace some time slots with empty slots





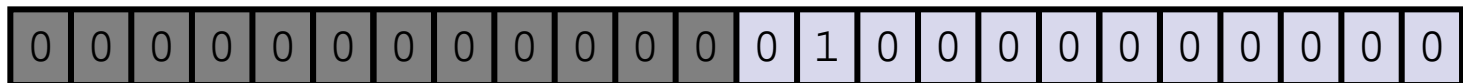
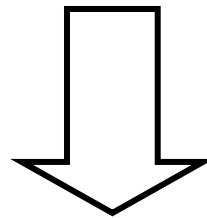
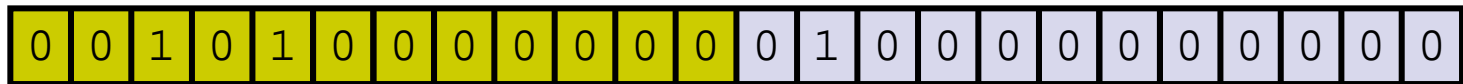
# Customized Genetic Operators

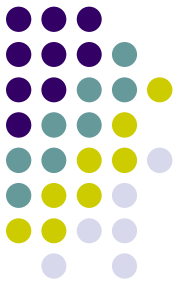


- Mutation

- Slot-level granularity

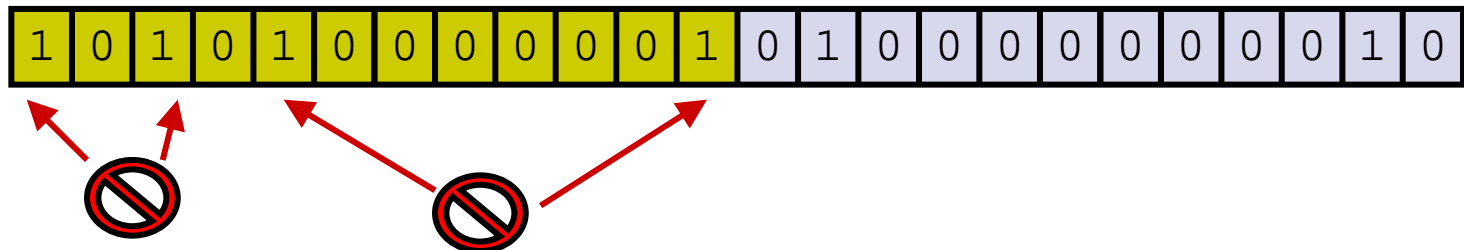
- Scramble some of the time slots
- Replace some time slots with a copy of other ones
- **Replace some time slots with empty slots**



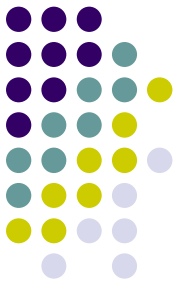


# Handling Constraints

- What if a genetic operator generates an unfeasible individual?

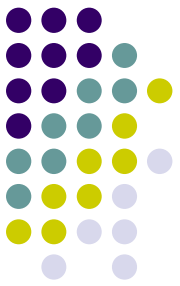


- The basic GA cannot handle constraints
- Two possible approaches
  - Try to **repair** the unfeasible individual
  - Let unfeasible individuals survive, but **penalize** them in the fitness function



# Handling Constraints

- The solution depends on how difficult is to enforce the constraint
  - Direct compatibility constraints can easily be **repaired** by randomly deactivating some of the conflicting links
  - Actually, they are also fundamental to derive our analytical formulation, so it is important that every individual respects them.

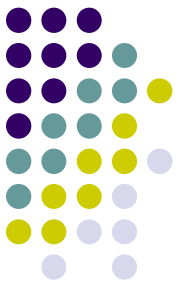


# Handling Constraints

- **Flow constraints** and **physical interference constraints** are enforced via penalties
- We weigh in a proper penalty function
  - The number of unsatisfied interference constraints
  - The number of undelivered packets
- This results in

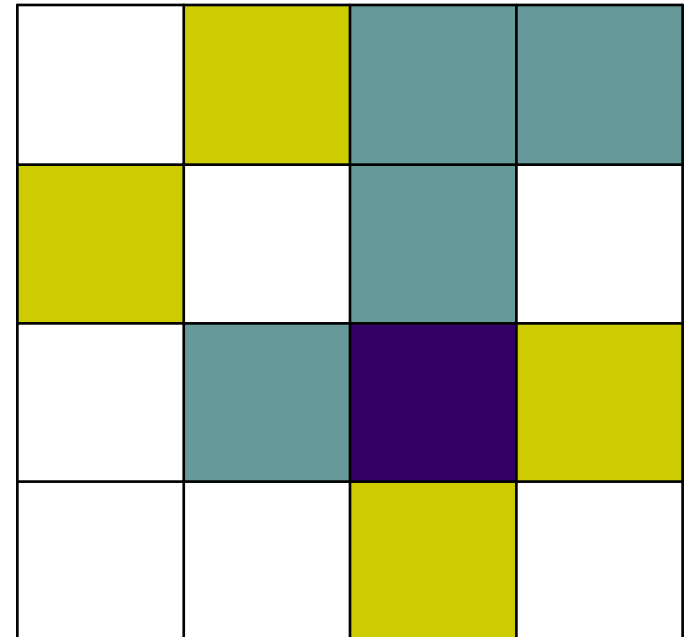
$$\rho = \sum_{i \in \mathcal{N}} q_i(0) - \sum_{i \in \mathcal{Y}} q_i(T) + \sum_{t=0}^{T-1} \sum_{(i,j) \in \mathcal{E}} p_{ij}(t)$$

where  $p_{ij}=1$  each time the SIR is violated.

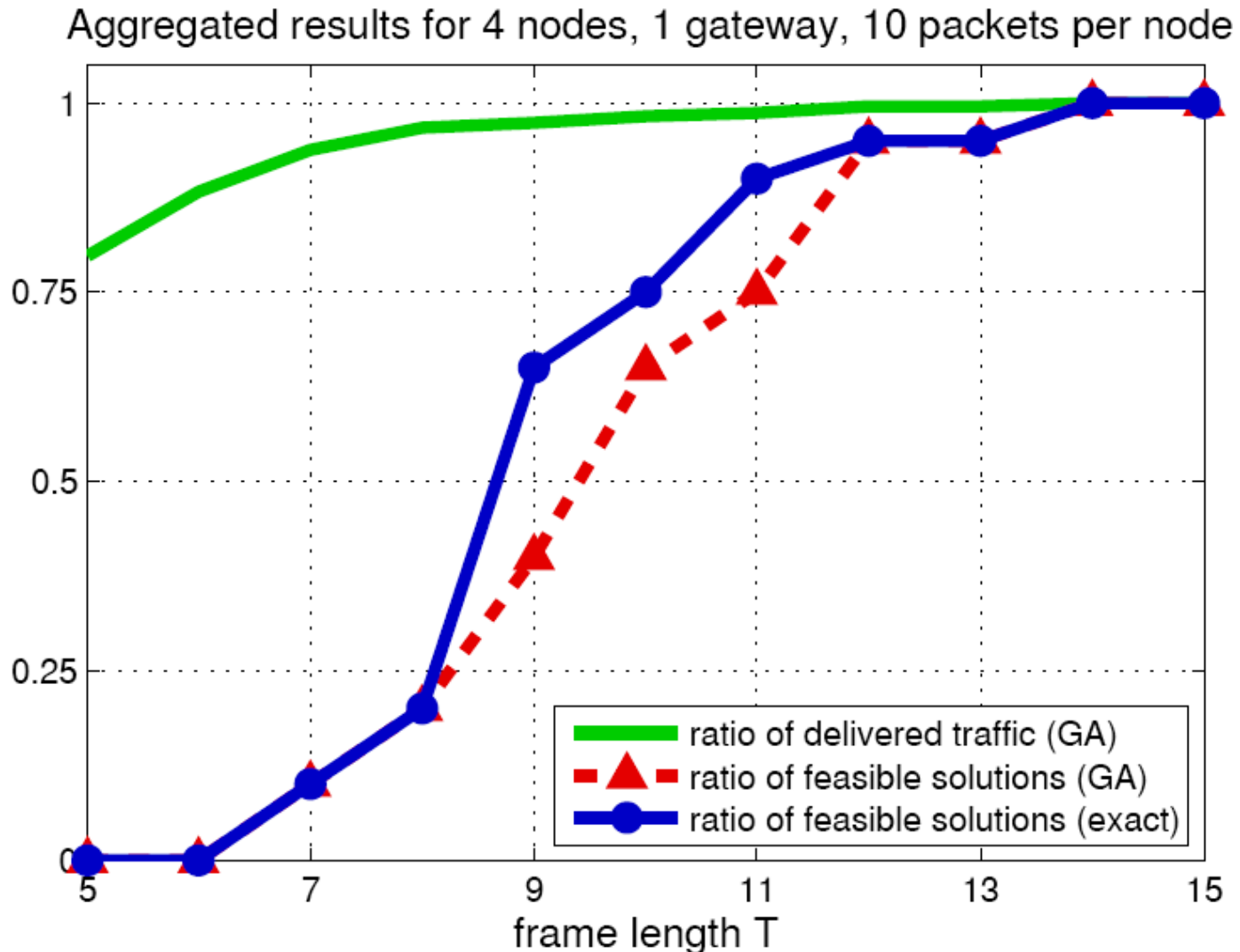
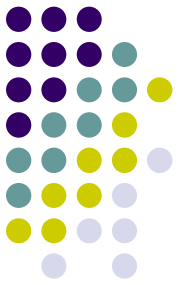


# Numerical results

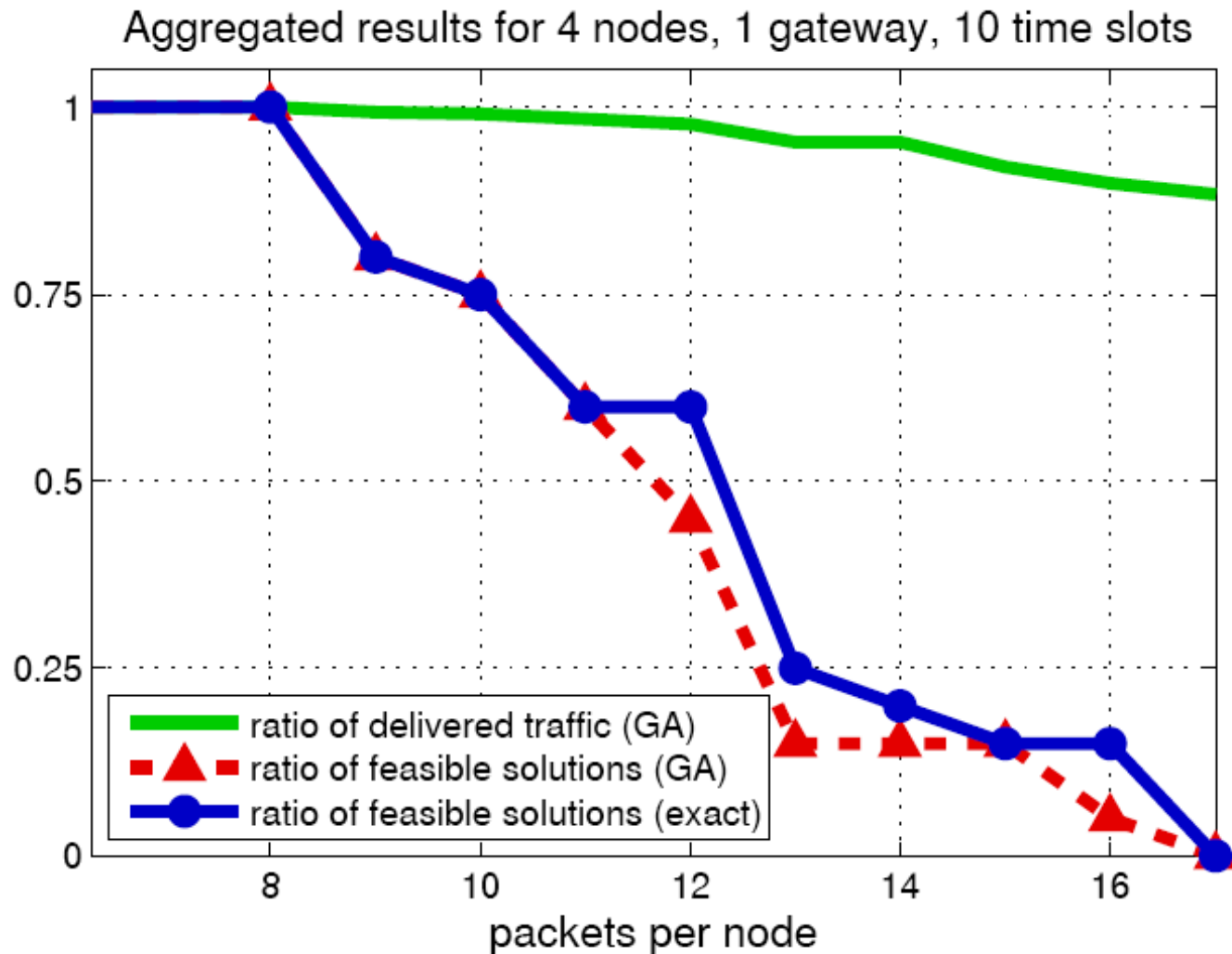
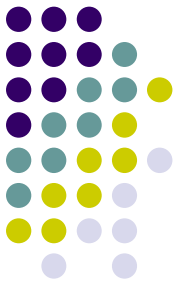
- 5 – 9 nodes in a grid with  $35\text{m} \times 35\text{m}$  squares
- Random placements within a colored square.
- Gains proportional to  $d^{-3.5}$
- 10 topology instances.
- Each instance run 5 times
- SIR target  $\gamma = 3.0$
- Compared with exact results (only for feasibility in small networks)

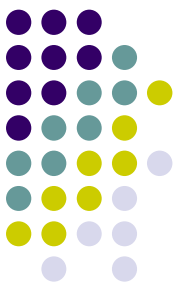


# Delivery of fixed load over a variable time – period (N=5)



# Delivery of variable load over a fixed time – period (N=5)

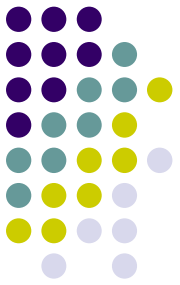




## To sum up...

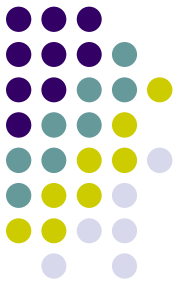
- ↑ Genetic Algorithms look promising to approach JRS problems.
- ↓ This approach works for small networks...
- ↓ ...and needs centralized knowledge.
- Future goal: better genetic representation.
- Future goal: insert expert knowledge to obtain better (distributed?) solutions.





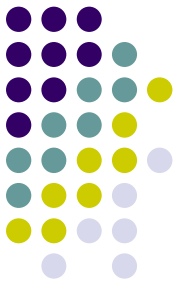
# Outline

- Wireless Mesh (Multi-hop) Networks
- Issues in Wireless Mesh Networks
  - Scheduling
  - Routing
  - Cross-layer JRS
    - Interference models
    - JRS through Genetic Algorithms
- **Future Extensions**



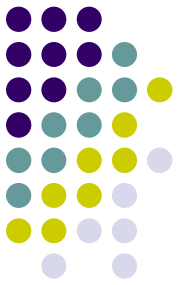
# Interference models

- The physical interference model is better but also harder to apply than the protocol model.
- PHY layer knowledge could be mapped into the nodes in order to simplify the physical interference model.



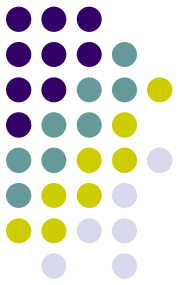
# Distributed management

- We discussed a centralized network management.
- Is it possible to make it distributed, to some extent?
- Which is the price to pay?
- Possible approaches based on game theory?



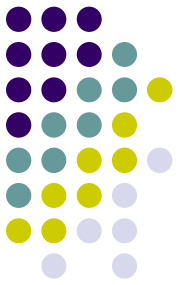
# Network monitoring

- The system can exploit management through agents sent throughout the network.
- It can be interesting to implement probing policies for QoS routing metrics and to gain knowledge about physical layer metrics.



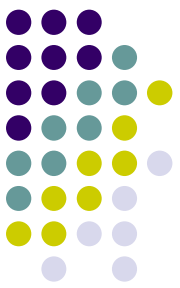
# Autonomic management

- Even though nodes are stationary, network conditions vary: channel, traffic, failures.
- How WMNs can react to these changes?
- How WMNs can organize themselves to react to failures?
- An interesting point for control and computational intelligence techniques.



# Scheduling failures

- We have focused on perfect schedulers.
- What if a transmission fails?
- Evaluation of ARQ-like techniques (e.g., Hybrid ARQ) on WMNs can be interesting.
- This is also connected with cooperation and network coding.



# Services and cost models

- Economics of WMNs is an open field.
- Services to be supplied via WMN have a potentially huge market.
- Combination of multiple WMNs is challenging (multiple operators, multiple strategies)
- Packet relaying in multi-hop is becoming a classical economic case.
- Applications to cooperation, game theory...