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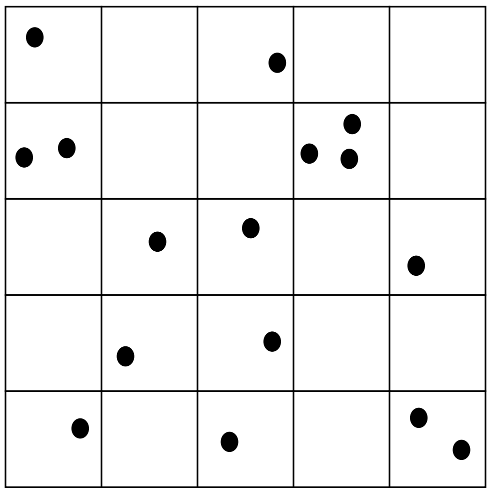
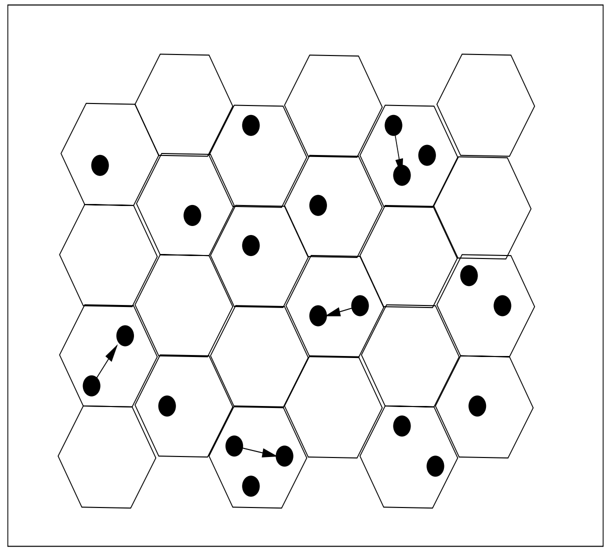
Improving Delay in Mobile Ad-Hoc Networks Via Redundant Packet Transfers





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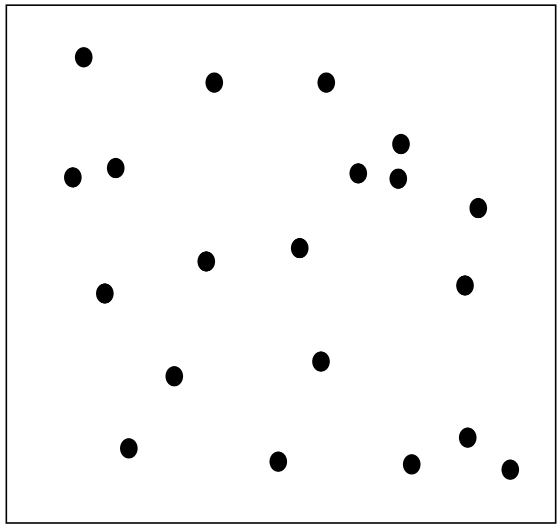
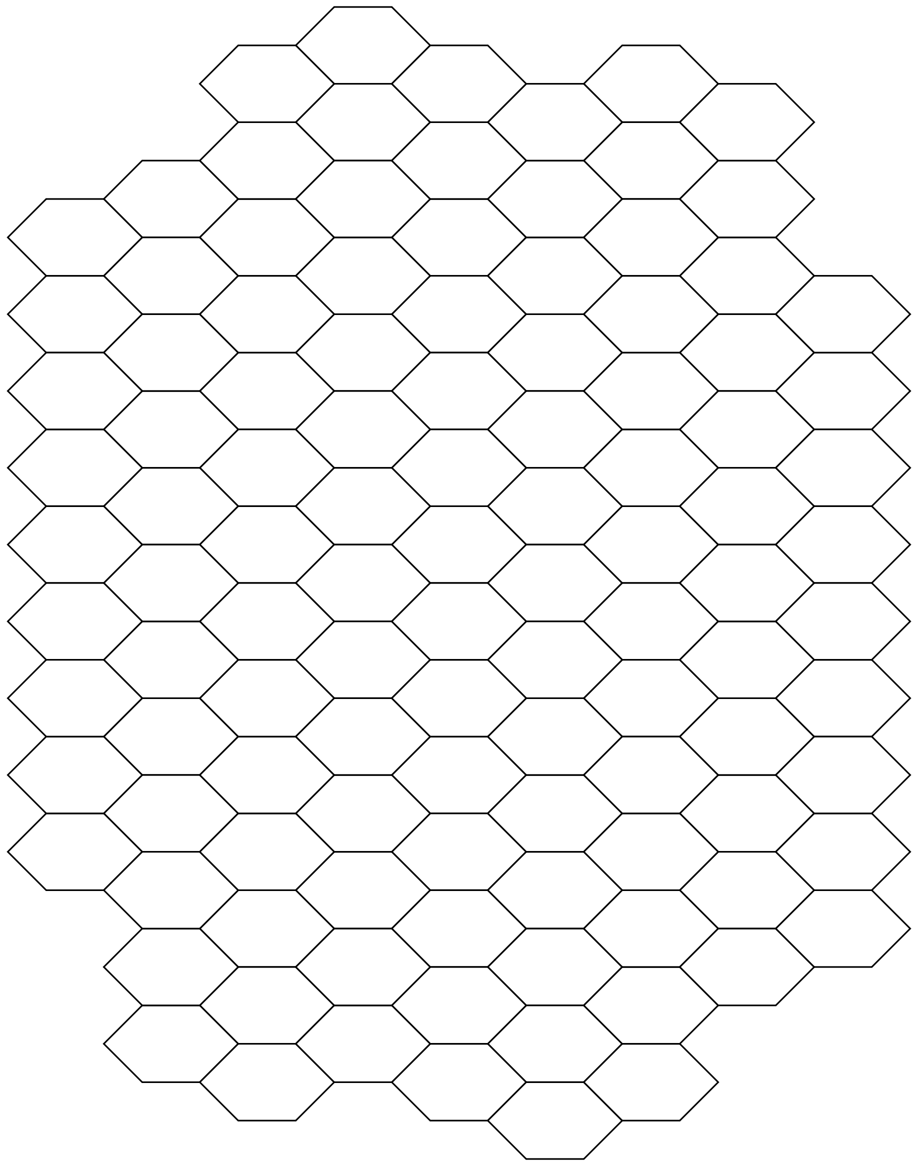
Ad-Hoc Wireless Network Scenario:



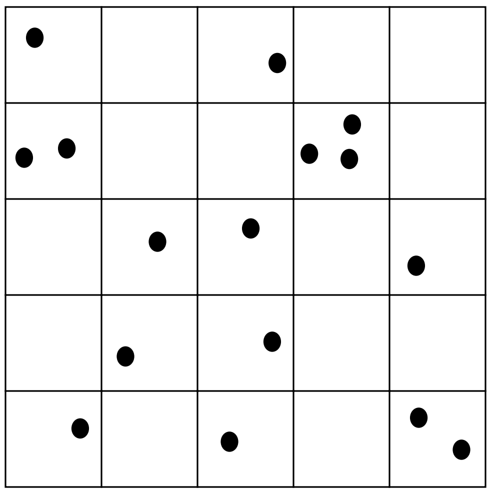
Network of area A meters^2
N mobile users

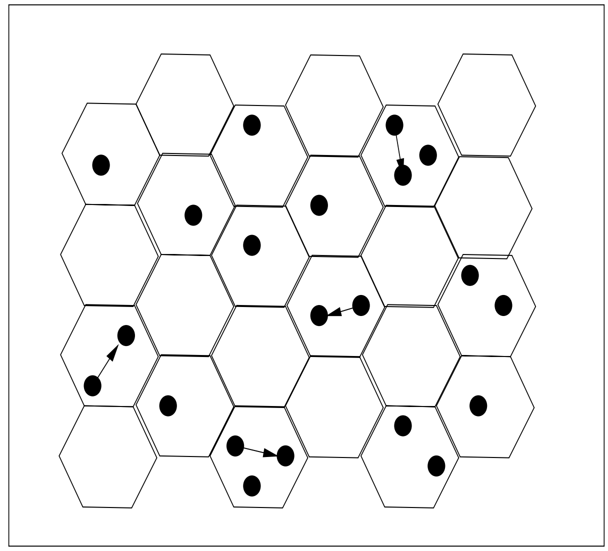
<u>Precedents</u>:
Static Network: Gupta and Kumar [1998, 2000]
Mobile Network: Grossglauser and Tse [2001]

Network:	Capacity	Delay
Static	$O(1/\sqrt{N})$	
Mobile	O(1)	



Cell Partitioned Networks:

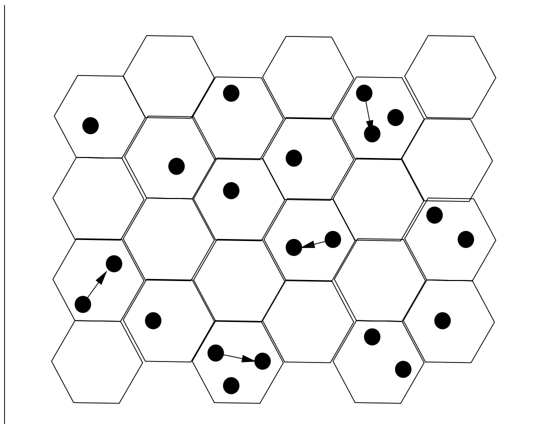




Network Description:
N = Number of users
C = Number of cells
$d = N/C$ = user/cell density

Cell Partitioned Network:
- -Timeslotted System
- -Only one Packet Transmission per Cell in a given timeslot
- -Multiple Cells can be activated simultaneously

(These are the “physical layer” constraints).



N = Num users

C = Num cells

$d = N/C$ = User/cell density

Mobility model:
Full iid mobility, steady state probability $1/C$

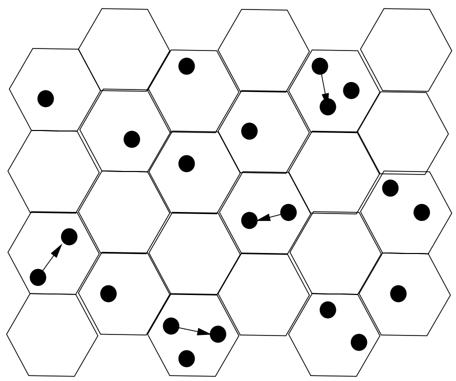
iid mobility model is an over-simplification, but provides situation where:

-Network topology dramatically changes every timeslot

-Can't use fixed routing schemes: Must rely on robust routing and scheduling.

Subject to the "physical layer" constraints and the mobility model, what is the network capacity and delay?

Network Capacity:



N = Num users

C = Num cells

$d = N/C$ = User/cell density

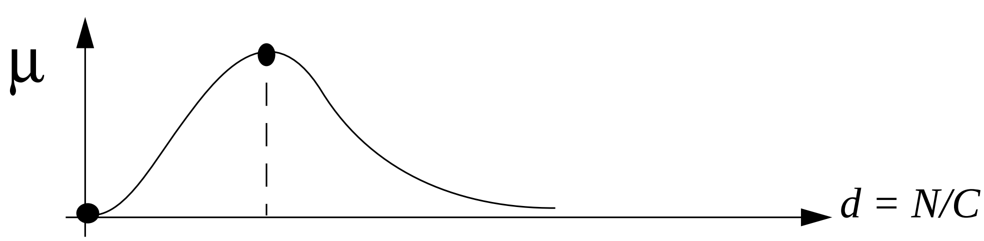
Users: $1 \leftrightarrow 2,\ 3 \leftrightarrow 4,\ 5 \leftrightarrow 6,\ ...,N-1 \leftrightarrow N$

Theorem 1: Each user can transmit with capacity $\lambda < \mu$, where:

$$\mu = \frac{(1 - e^{-d} - d e^{-d})}{d} + O\left(\frac{1}{N}\right) \quad \square$$

(fix $d = N/C$ => O(1) capacity regardless of N)

*Optimal user/cell density:



d* = 1.7933 users/cell , μ* = 0.1492 packets/slot

$\lambda \leq \mu$ necessary.
$\lambda < \mu$ sufficient.

Capacity is achievable using a modified version of the Grossglauser-Tse 2-hop Relay algorithm.

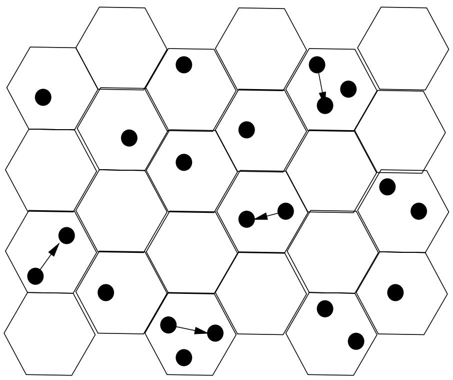
Algorithm and iid mobility model admits a nice, ***exact queueing analysis***:

Exact End-End Network Delay-- If Exogenous input stream to source *i* is Bernoulli with rate λ_i:

$$E[W_i] = \frac{N - 1 - \lambda_i}{\mu - \lambda_i}$$

=> stable when all users have $\lambda_i \leq \mu$.

This is a scheme that gives *O(N)* delay without using redundancy. What if redundancy is in the picture?



N = Num users

C = Num cells

$d = N/C$ = User/cell density

Theorem: Redundant packet transfers and/or perfect knowledge of future cell locations of all users does not increase network capacity.

But what about delay?

Theorem: If no redundancy is used, no scheduling algorithm can achieve better than $O(N)$ delay.

Proof: Consider sending a single packet...

How can redundancy reduce delay?

Consider 2-hop schemes:

Fundamental Delay Bounds:

<u>Theorem</u>: No scheduling algorithm with or without redundancy can do better than $O(N^{1/2})$ delay.

Proof idea: Consider single packet to be sent from source to destination. Time to reach dest. is related to T_n:

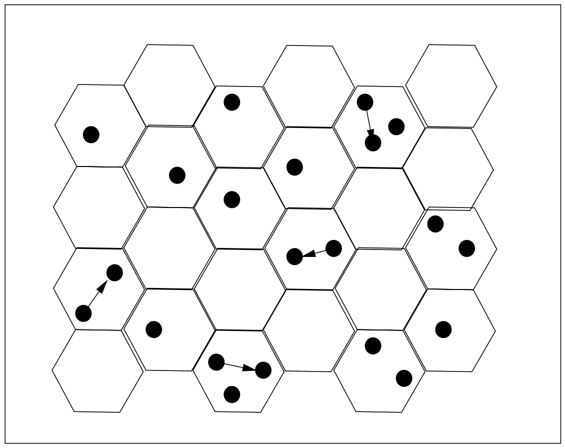
Define: T_n =

$$1 + \left(1 - \frac{1}{n}\right) + \left(1 - \frac{1}{n}\right)\left(1 - \frac{2}{n}\right) + \left(1 - \frac{1}{n}\right)\left(1 - \frac{2}{n}\right)\left(1 - \frac{3}{n}\right) + \ldots$$

$$+ \ldots + \left(1 - \frac{1}{n}\right)\left(1 - \frac{2}{n}\right)\ldots\left(1 - \frac{n-1}{n}\right) + 0$$

Lemma:

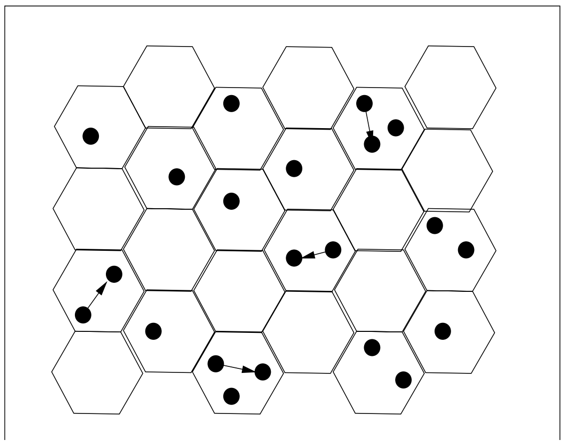
$$\frac{n^{1/2}}{e} \le T_n \le 2n^{1/2}$$



Normalize Capacity: $\mu = 0.1492 = O(1)$

	Capacity	Delay
No Redundancy:		
Redundancy: 2-hop		
3-hop		
N-hop		

We design a scheduling protocol to achieve the $O(N^{1/2})$ delay bound. The protocol (necessarily) uses duplicate packet transfers.



Complications to Overcome:

1. this is not just a single packet transfer -- packets arrive randomly as a data stream.

2. All sessions must use network simultaneously.

3. Remnant versions of a packet may float around and create extra congestion.

Partial Feedback Scheme with Redundancy:

Packets labeled with *SN* numbers 1,2,3,4,...
In-Cell feedback: In each cell, the destination sends a *request number RN* to the transmitter just before transmission.

$\sqrt{N}$ Scheduling Protocol: The 2-hop relay algorithm is used to establish transmission opportunites for all users. Then:

1) Users send each packet $\sqrt{N}$ times, once each time we see a new relay node.

2) When a user is scheduled to transmit a relay packet to its destination, the following handshake is performed:

- The destination delivers its current *RN* number for the packet it desires.

- The transmitter deletes all packets in its buffer intended for this destination which have *SN* numbers lower than *RN*.

- The transmitter sends packet *RN* to the receiver. If the transmitter does not have the requested packet *RN*, it remains idle for that slot.

Theorem: This protocol achieves the optimal $O(\sqrt{N})$ delay, with data rates of all users equal to $\lambda = O(1/\sqrt{N})$.

Conclusions:

Scheme	Capacity	Delay
no redundancy		
redundancy 2-hop		
redund. multi-hop		

Observation: Delay/Rate >= $O(N)$
Conjecture: This is a necessary condition.

Fundamental Capacity-Delay Tradeoffs with redundant packet transfers:
High Redundancy =>low delay, but low capacity

Exact Capacity for any number of users *N*:

(N even): $$\mu = \frac{p+q}{2d}$$

where: $$d = N/C$$

$$p = 1 - \left(1 - \frac{1}{C}\right)^{N} - \frac{N}{C}\left(1 - \frac{1}{C}\right)^{N-1}$$

$$q = 1 - \left(1 - \frac{1}{C^2}\right)^{N/2}$$

Let: λ_{ij} = Rate user i sends packets destined for user j.

K = max number users a source communicates with (i.e., for all i, at most K of the λ_{ij} values are nonzero).

Symmetric Capacity Region: (achieved by modified version of the Grossglauser-Tse Relay alg)

$$\sum_j \lambda_{ij} \le \frac{(1 - e^{-d} - de^{-d})}{2d} + O\left(\frac{K}{N}\right) \quad \text{for all } i$$

$$\sum_i \lambda_{ij} \le \frac{(1 - e^{-d} - de^{-d})}{2d} + O\left(\frac{K}{N}\right) \quad \text{for all } j$$