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

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Ad-Hoc Wireless Network Scenario:

Network of area $A \text{ meters}^2$
$N$ mobile users

Precedents:
Mobile Network: Grossglauser and Tse [2001]

<table>
<thead>
<tr>
<th>Network</th>
<th>Capacity</th>
<th>Delay</th>
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</thead>
<tbody>
<tr>
<td>Static</td>
<td>$O(1/\sqrt[N]{N})$</td>
<td></td>
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<tr>
<td>Mobile</td>
<td>$O(1)$</td>
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</tbody>
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Cell Partitioned Networks:

Network Description:
$N = \text{Number of users}$
$C = \text{Number of cells}$
$d = \frac{N}{C} = \text{user/cell density}$

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).
**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:

Users: 1 ↔ 2, 3 ↔ 4, 5 ↔ 6, ..., N − 1 ↔ N

Theorem 1: Each user can transmit with capacity λ < μ, where:

\[
\mu = \frac{(1 - e^{-d} - d e^{-d})}{d} + O\left(\frac{1}{N}\right)
\]

(fix \( d = N/C \) ⇒ O(1) capacity regardless of \( N \))

*Optimal user/cell density:

\[ d^* = 1.7933 \text{ users/cell}, \ \mu^* = 0.1492 \text{ packets/slot} \]
$\lambda \leq \mu$ 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 $\lambda_i$:

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

$\Rightarrow$ 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?
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:

**Theorem:** 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:
\[
\frac{n^{1/2}}{e} \leq T_n \leq 2n^{1/2}
\]
Normalize Capacity: $\mu = 0.1492 = O(1)$

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<tr>
<td>No Redundancy:</td>
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<tr>
<td>Redundancy:</td>
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<tr>
<td>2-hop</td>
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<tr>
<td>3-hop</td>
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<tr>
<td>N-hop</td>
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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 opportunities 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:

<table>
<thead>
<tr>
<th>Scheme</th>
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<tr>
<td>no redundancy</td>
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<tr>
<td>redundancy 2-hop</td>
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<td>redund. multi-hop</td>
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Observation: Delay/Rate \( \geq O(N) \)
Conjecture: This is a necessary condition.

Fundamental Capacity-Delay Tradeoffs with redundant packet transfers:
High Redundancy \( \Rightarrow \) low delay, but low capacity
Exact Capacity for any number of users $N$:

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

where:
\[ d = \frac{N}{C} \]

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

Let: $\lambda_{ij} =$ 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 $\lambda_{ij}$ values are nonzero).

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

\[ \sum_j \lambda_{ij} \leq \frac{\left( 1 - e^{-d} - de^{-d} \right)}{2d} + O\left( \frac{K}{N} \right) \quad \text{for all } i \]
\[ \sum_i \lambda_{ij} \leq \frac{\left( 1 - e^{-d} - de^{-d} \right)}{2d} + O\left( \frac{K}{N} \right) \quad \text{for all } j \]