Load Balanced Short Path Routing in Wireless Networks

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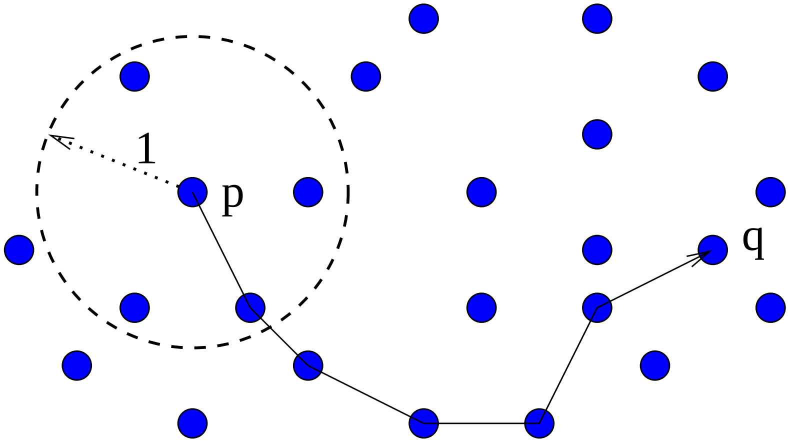
Ad hoc wireless networks

A set of nodes in the plane, any two can communicate directly if they are within Euclidean distance 1.



- No central control.
- Highly dynamic.
- Nodes are energy constrained.

Energy-aware routing

Energy concern:

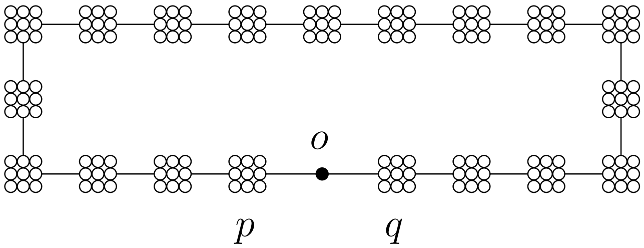
- Energy consumption is dominated by communication.
- Nodes on the shortest paths are heavily loaded.

The ideal routing algorithm:

- O(1) stretch factor: number of hops of the path v.s. the shortest distance;
- O(1) load balancing ratio: maximum traffic passing any node v.s. offline optimum.

Short path routing v.s. load balanced routing

Generally, short path routing and load balanced routing are contradictory to each other. Example: any short path from p to q has to pass o.



Our contribution: a routing algorithm inside a band of width $\leq \frac{\sqrt{3}}{2}$:

- Near optimum: stretch factor: 4, load balancing ratio: 3.
- Distributed and local.
- Low space and time complexity.
- Efficient insertion and deletion of nodes.

Why a narrow band?

- A practical model for many applications
    - vehicles on a highway
    - people on a street
- and, we know how to solve it.

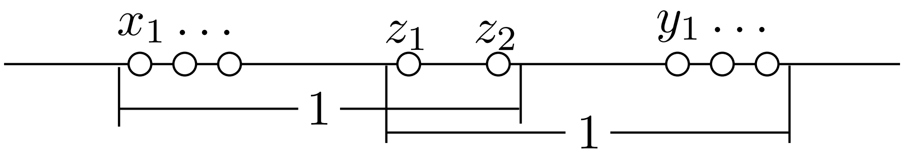
Outline:

- Load balanced routing on a line
- Load balanced routing in a narrow band

Related work

- Online virtual circuit routing.
  - arbitrary graph.
  - centralized algorithm.
  - AAP-algorithm by Aspnes et. al.
- Energy-aware routing in wireless networks.
  - little theoretical bound on the performance.

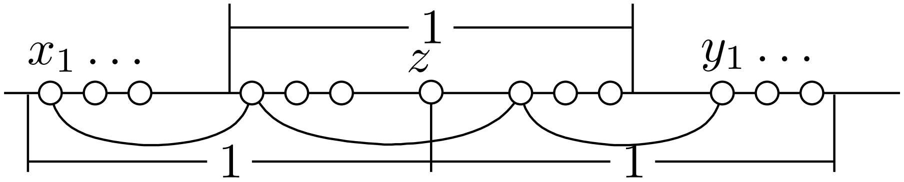
Load balanced routing on a line is hard



packets: $x_i \rightarrow y_i$, size s_i

$\Rightarrow$ the perfect load balancing is when s_i's can form two equal sums

$\Rightarrow$ optimal load balanced routing is NP-hard.



packets: $x_i \rightarrow y_i$

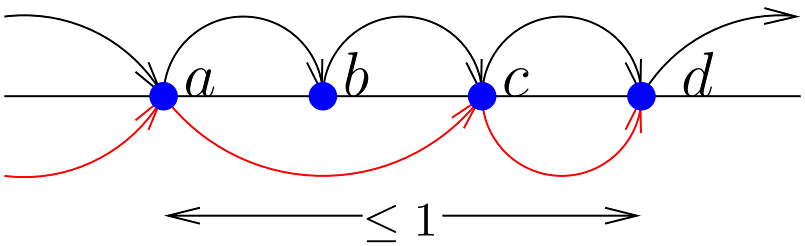
$\Rightarrow$ the shortest path from x_i to y_i passes node z

$\Rightarrow$ It's impossible to minimize both the stretch factor and LB ratio.

Requests with unit packet size

GREEDY1: Send the packet to the furthest node in the communication range whose load is NOT the maximum.

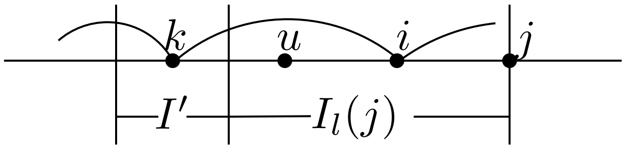
Claim: For 4 adjacent nodes a, b, c, d along a routing path, d is at least distance 1 away from a. Stretch factor ≤ 3.



GREEDY2: Do 1-hop look-ahead: delete b if a and c are visible. Stretch factor ≤ 2.

Requests with unit packet size

GREEDY2 has load balancing ratio ≤ 2. Suppose after k sends the packet to i, i has the max load $\ell(i)$.



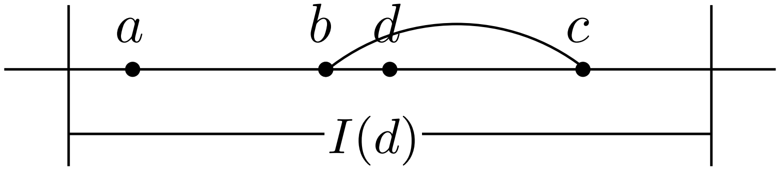
- The immediate right neighbor j of i is NOT visible to k.
- All the m nodes in the left visible range $I_\ell(j)$ of j, except i, has load exactly $\ell(i) - 1$. Total load in $I_\ell(j)$ =$(m-1)(\ell(i)-1)+\ell(i)$.
- GREEDY2 uses ≤ 2 nodes in $I_\ell(j)$
  $\Longrightarrow$ No. Req. =$(m\ell(i) - m + 1)/2$.
- $\text{load}(\text{OPT}) \geq (m\ell(i) - m + 1)/(2m)$
  $\Longrightarrow \text{load}(\text{GREEDY2}) \leq 2\text{load}(\text{OPT}) + 1$.

Requests with variable packet sizes

A pair of nodes bc within distance 1 is a bridge for a if b is inside a's visible range while c is not.

GREEDY3

- a asks the furthest node d for the lightest bridge bc.
  - both b, c are visible to d.
- a routes the message through bc.
- Shortcut the path if two non-adjacent nodes are visible.



Similarly, GREEDY3's stretch factor is less than 2.

Requests with variable packet sizes

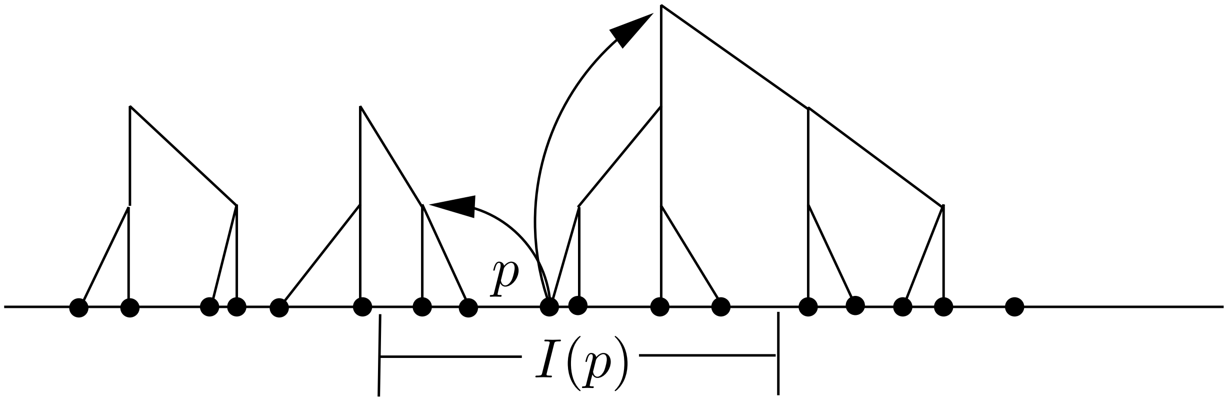
GREEDY3's load balancing ratio is ≤ 3.

Consider the ith packet with size ℓ_i, if load$(bc) + \ell_i > 3\mathrm{OPT}_i$,

- A node u is heavy if its load is the load of a bridge uv of a.
- GREEDY3 routes through the lightest bridge bc of a.
- GREEDY3 uses ≤ 2 heavy nodes.
- OPTIMAL algorithm uses ≥ 1 heavy node.
- $\mathrm{OPT}_{i-1} \geq \frac{\mathrm{load}(bc)}{2} > \frac{(3\mathrm{OPT}_i - \ell_i)}{2} > \mathrm{OPT}_i, \Longrightarrow$ contradiction.

Distributed implementation

Maintain a binary search forest in a distributed way.

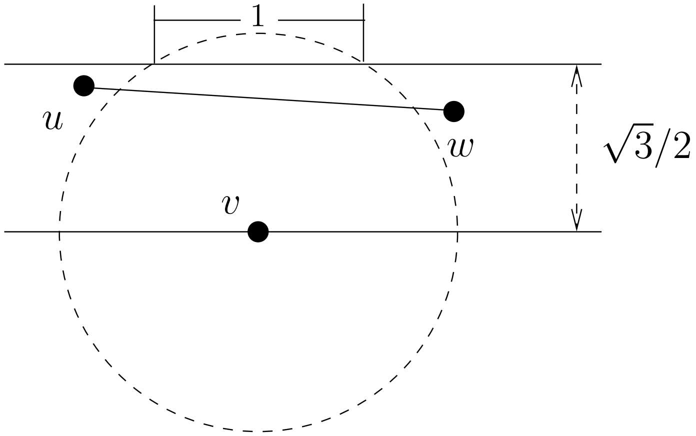


Complexity: $h_x(p)$: number of nodes within distance x from p.

- space: $O(\log h_1(p))$.
- time: $O(\log h_1(p))$ (unit size) $O(\log^2 h_2(p))$ (variable size).
- node insertion/deletion: $O(\log h_1(P))$ time.

Routing inside a narrow band

Inside a band with width $\leq \frac{\sqrt{3}}{2}$, there is a rough linear order of the nodes: for any three nodes u, v, w from left to right, if u, w are visible, then one of them is visible to v.

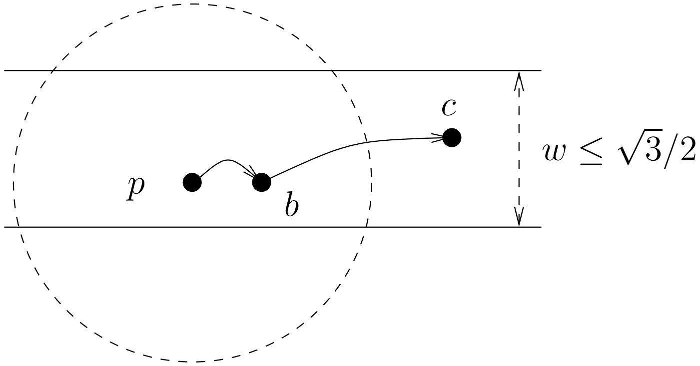


So the routing direction is obvious: route the packet to the left or right.

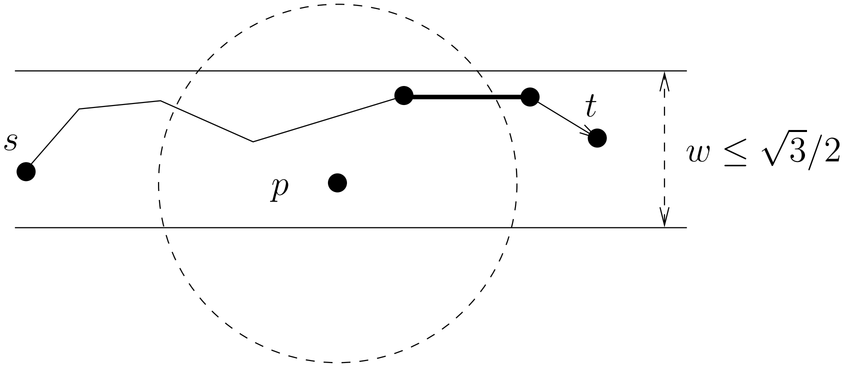
Question: to achieve load balancing ,which node to route to?

Routing in a narrow strip

GREEDY4: p routes through the lightest bridge bc.



Bridge bc;

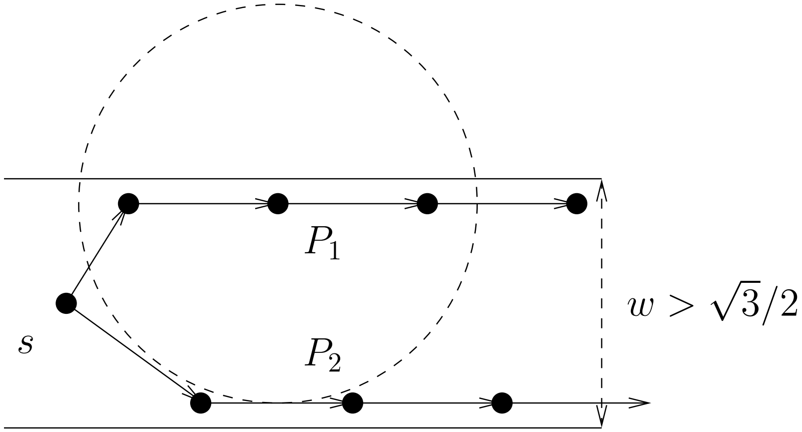


GREEDY4 can't stuck at p.

GREEDY4 guarantees delivery and has stretch factor ≤ 4 and load balancing ratio ≤ 3.

Routing in a wide band?

For routing in a strip with width more than $\leq \frac{\sqrt{3}}{2}$, any routing algorithm with only local information does NOT have bounded load balancing ratio.

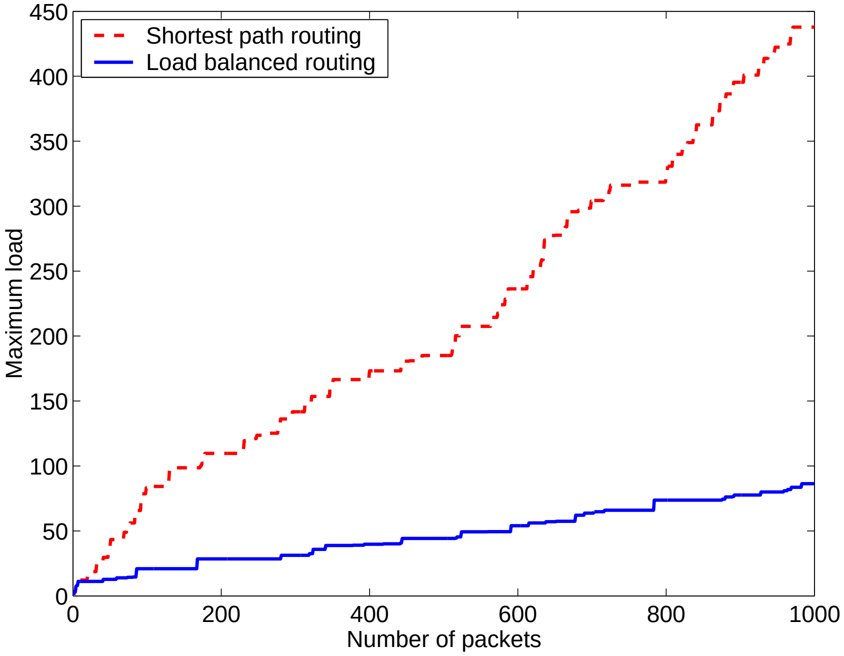


With only local information, s doesn't know which one of P_1, P_2 is more heavily loaded.

Simulation under random traffic

1000 random nodes in $[0, 100]$, communication radius: 5.

The maximum load in GREEDY3 v.s. Shortest path routing ≈ 5.

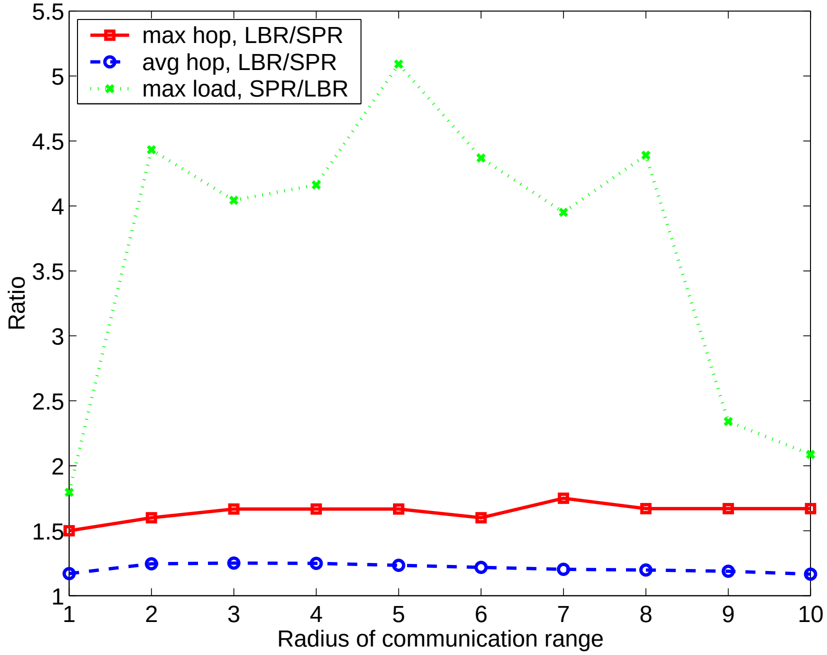


Simulation under random traffic

1000 random nodes in $[0, 100]$, communication radius: $[1, 10]$.

Worst & average stretch factors of GREEDY3.

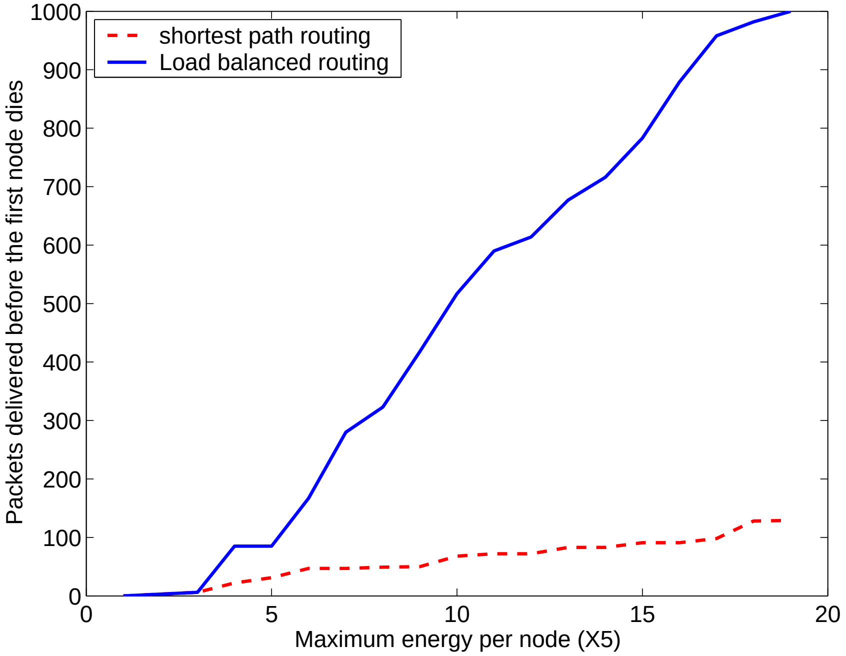
Little sacrifice on the stretch factor, huge gain on load balancing.



Limited energy, random traffic

1000 random nodes in $[0, 100]$, energy per node: [0, 90].

Number of packets delivered in GREEDY3 v.s. Shortest path routing, before the first node dies.



Conclusion and Future Work

Contribution: short path load balancing routing algorithm for nodes inside a narrow band.

- Near optimum: stretch factor: 4, load balancing ratio: 3.
- Distributed and local.
- Low space and time complexity.
- Efficient insertion and deletion of nodes.

Future work

- Other node distributions, e.g. on grid.

Thank You!