Probabilistic Algorithms for Cost-based Integrated MAC and Routing in Wireless Sensor Networks

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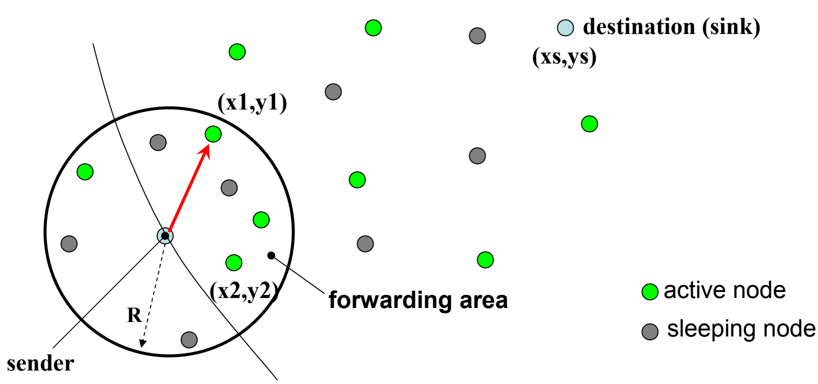
A possible approach: Geographical Routing

- **Pros:** relay nodes are selected "on the fly" based on node *advancements*
- **Cons:** each node must know its own geographical position (or its estimate); possible dead ends



An alternative approach: Hop Count Routing

- The role of node coordinates is substituted by *hop count values*
  Hop Count: *"the minimum number of TX that are needed to get to the sink using a multi-hop TX technique"*

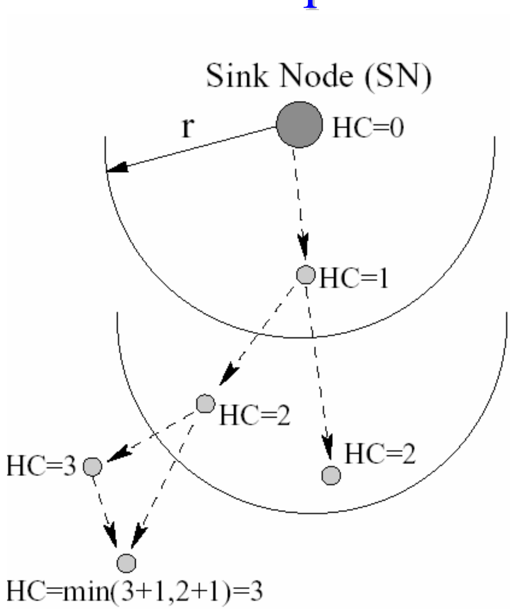
- A Hop Count Field can be easily set up and (periodically) updated → No need to perform costly operations such as position estimation.

- Routing as a *Sequential Decision Problem*, where we use *Hop Counts* (HC) to assess the direction to be followed by each packet

  → HCs give an indication of the *"distance" to the sink*
  → HCs contain information about the *connectivity structure*

Routing over virtual coordinates (HCs)

Hop Count Field



- **Periodically refresh the hop count field**
- **Propagate hop count information and take the minimum at every node**

Path and Cost Models

- Path: is an ordered list

$$P = \{s, r_1, r_2, \ldots, r_n, d\}$$

where s and d are referred as the source and the destination node

- The path cost is defined as

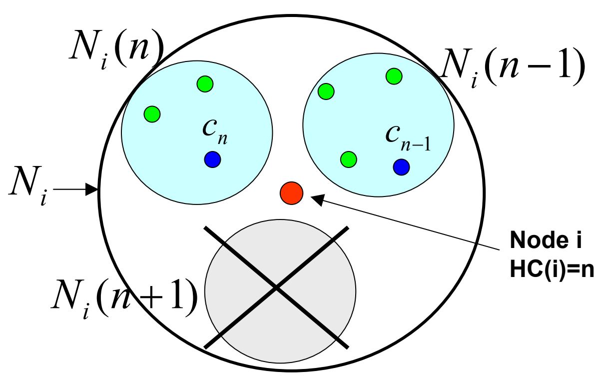
$$C(P) = c_{sr_1} + \sum_{i=1}^{n-1} c_{r_i r_{i+1}} + c_{r_n d}$$

where c_{ij} is the cost associated with link (i,j).

If TX power is constant at every sending node i → $c_{ij} = c_j$

Hop Count Greedy Forwarding

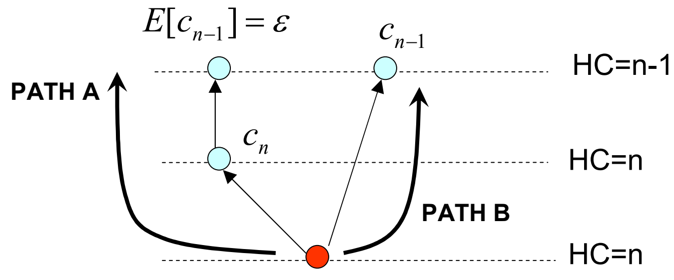
- c_n lowest cost node in set $N_i(n)$
- c_{n-1} lowest cost node in set $N_i(n-1)$
- Hop Counts (HCs) are used for the next hop selection
- Forwarding to a node in $N_i(n+1)$ is *"inefficient"*



Statistically Assisted Greedy Forwarding: example for a forwarding cycle of length 2

- PATH A is preferable over PATH B if $c_n + \varepsilon < c_{n-1}$

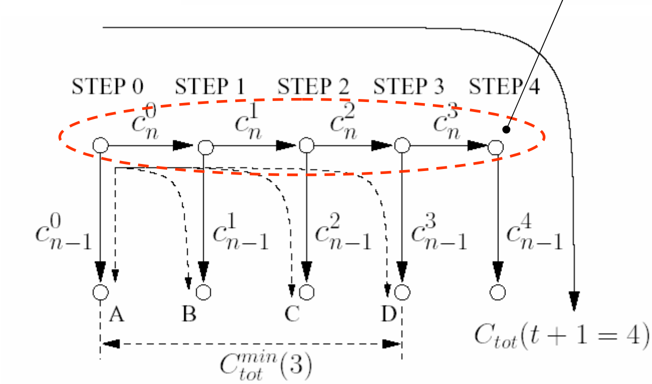
Expected value of the minimum cost for the out of range node with HC n-1



Multi-Stage Hop Count Routing Scheme

- **MULTI-STAGE policy** → forwarding decisions are made based on current (local) costs, future cost estimates (ε) and on *the past cost history*

$$\mathcal{B}_2 = \left\{ X_t : C_{tot}^{min}(t) - C_{par}(t+1) \leq \mathcal{E} \right\}$$



Integrated Routing and MAC

- The previous Hop Count based forwarding scheme is used to make routing decisions

- We want to obtain the information about in range nodes (c_n and c_{n-1}) ***on the fly*** in order to adapt to the time varying network conditions

- c_n and c_{n-1} are the in range nodes with the lowest cost with HC n and n-1

- We need to set up a channel contention phase in order to obtain the wanted cost information so as to make the forwarding decision

- **Goals: low delay and good relay selection (low cost)**

Two possible approaches

In both cases, nodes respond to a RTS with given prob.
1) Assume nodes as equivalent. The optimal node reply probability is given by (1/N case):

$$P_r(c) = \frac{1}{N}$$

2) Consider **node costs as uniformly and independently distributed (iid case)**. In this case it is reasonable for every node to independently reply with a probability given by:

$$P_r(c) = (1 - c)^{N-1}$$

A Better Solution:
keep the cost correlation into account

We assume: $$C_i = \overline{c} + \xi_i(\overline{c})$$

Logically → two phases cost selection criteria:

1) Select common cost component
2) Select additive noises for every node

Moreover:

$$\overline{c} \in U[0,1]$$
$$\xi_i \in U[-\alpha \cdot \overline{c}, \alpha \cdot (1-\overline{c})]$$

Access probabilities

With the previous cost model and a **given number N** of in-range devices →

we can derive, in close form, the probability for a given node of being the lowest cost node in the set

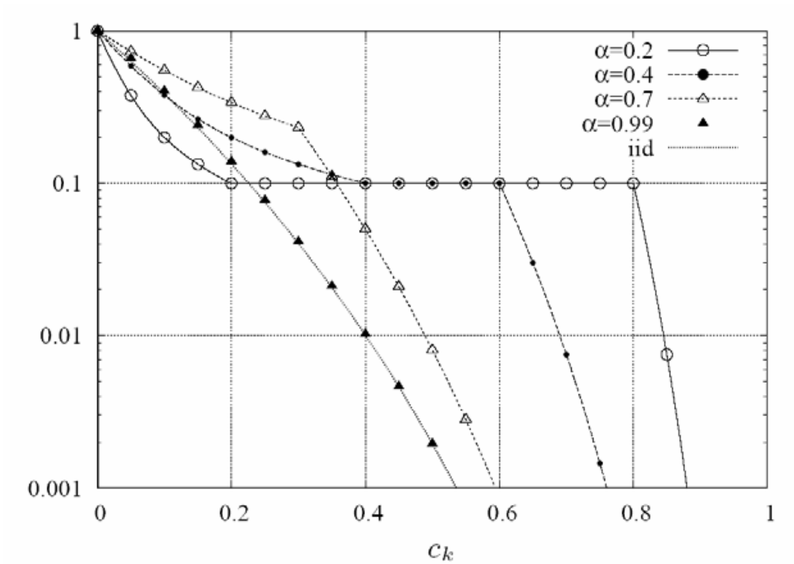
$$P^k_{min}(c_k)\Big|_{0<\alpha\leq 0.5} = \begin{cases} \dfrac{\alpha^N - (\alpha - c_k)^N}{c_k N \alpha^{N-1}} & 0 \leq c_k < \alpha \\ N^{-1} & \alpha \leq c_k \leq 1-\alpha \\ \dfrac{(1-c_k)^{N-1}}{N\alpha^{N-1}} & 1-\alpha < c_k \leq 1 \end{cases}$$

$$P^k_{min}(c_k)\Big|_{0.5<\alpha<1} = \begin{cases} \dfrac{\alpha^N - (\alpha - c_k)^N}{c_k N \alpha^{N-1}} & 0 \leq c_k < 1-\alpha \\ \dfrac{(1-c_k)^N - (\alpha - c_k)^N}{(1-\alpha) N \alpha^{N-1}} & 1-\alpha \leq c_k \leq \alpha \\ \dfrac{(1-c_k)^{N-1}}{N\alpha^{N-1}} & \alpha < c_k \leq 1 \end{cases}$$

$$P^k_{min}(c_k)\Big|_{\alpha=0} = \frac{1}{N}, \quad P^k_{min}(c_k)\Big|_{\alpha=1} = (1-c_k)^{N-1}.$$

We can therefore use these probabilities to decide whether a node should access the channel

Access probabilities



A MAC/Routing Integrated Solution

0) Init with ρ=0 (initial correlation estimate – min cost)
1) The source node sends a **REQ(n-1,ρ)**
2) Every node **(k) independently replies according to its access probability**

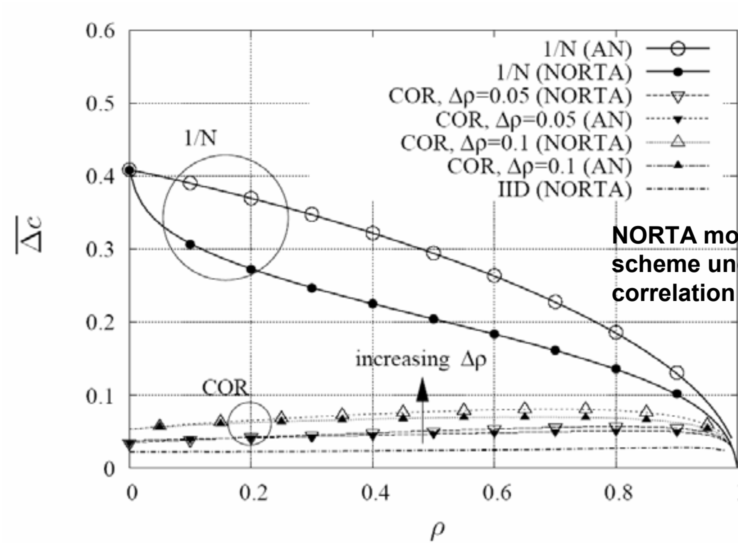
→ **silence (a)**
→ **collision (b)**
→ **winner (ends the contention)**

In cases (a) and (b) (→ update correlation estimate):

3) P **= min(1,ρ+**Δρ) and **go to 1)**

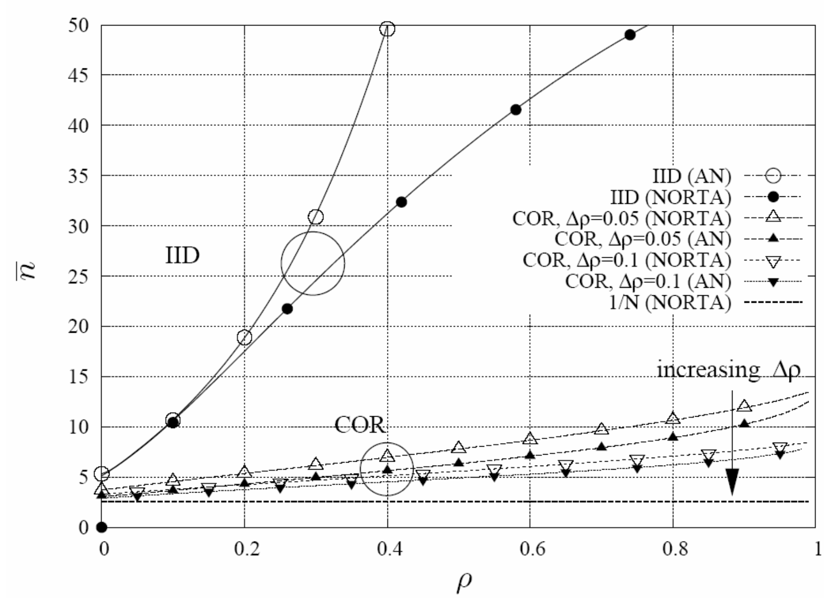
→ **Repeat the above steps for the nodes with HC n and make the forwarding decision**

MAC cost performance: cost difference with respect to the ideal case

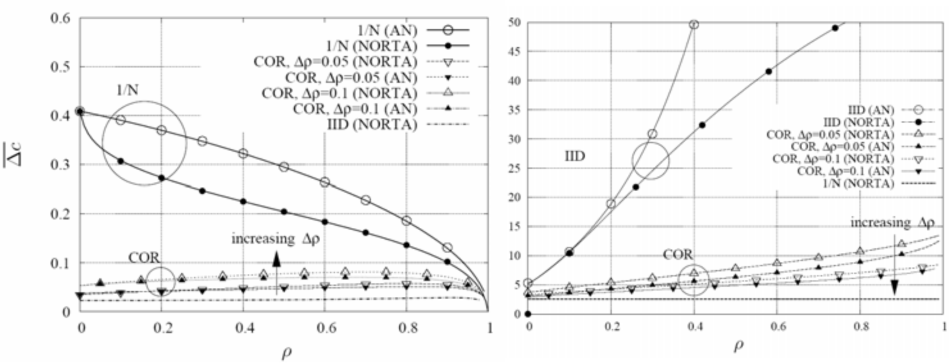


NORTA model to test our scheme under a general correlation structure

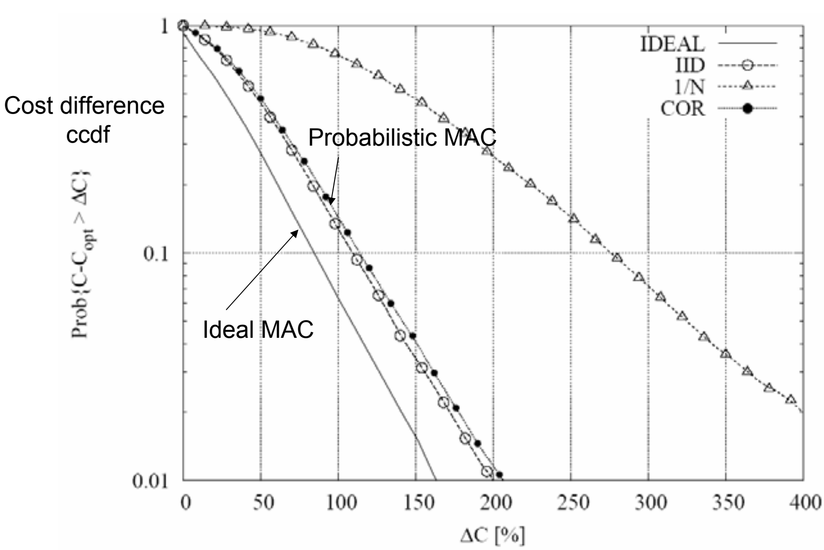
MAC delay performance: # of contention rounds



Cost-delay tradeoff



Multi-hop Performance: cost difference between on-line schemes and lowest cost paths



Conclusions

To sum up:

- Novel routing strategy based on Hop Counts and (first order) statistical information about out-of-range nodes
- Novel probabilistic cost aware contention phase
- Node costs → residual energies, congestion levels, etc.
- Node Hop Counts → to drive the selection toward delay efficient paths

Possible future work:

- The proposed MAC can be improved by exploiting the access probabilities in a more refined manner
- Data aggregation can be integrated in the approach to increase energy efficiency