Energy-Efficient Forwarding Strategies for Geographic Routing in Lossy Wireless Sensor Networks

K. Seada, M.Zuniga, A. Helmy and B. Krishnamachari
Department of Electrical Engineering
University of Southern California
The Wake-up Call

- **Idealized assumptions about channel characteristics**
  - Perfect coverage within a circular radio
    - Neither circular nor convex and often non-contiguous
  - Distribution of packet reception over distance is uniform
    - Non-uniform
  - Losses happen at long distances from the transmitter
    - Short distances too
  - Reliable Symmetric (wireless) links
    - Extremely unreliable asymmetric links, specially at lower power settings
  - Connectivity graph
    - Losses due to fading and obstacles are common and vary over time

- **New observations**
  - 3 distinct reception regions
    - connected, transitional, disconnected
Reception Regions

Each circle represents the link quality of a directed edge in the topology. Edges with the same distance can have very different reliability.
Lognormal Shadowing Model

Packet reception probability

Distance between nodes

Prp(x) = 1, x ≤ R
Prp(x) = 0, x > R
Geographic Routing

- Nodes need only to know the location information of their direct neighbors in order to forward packets
  - Each node forwards a packet to the neighbor that is closest to the destination (greedy forwarding)

- Discovery floods and state propagation not required (multihop)

- Assumptions
  - Sufficient network density
  - Accurate localization
  - High link reliability
Greedy Forwarding is loop-free

- S knows only position of
  - Itself
  - Its neighbors
  - Destination D
- S forwards to neighbor B closest to D
- Assume A_1 closest to D
- A_2 sends to A_3
- Contradiction, A_1 is closer
Problematic

- Unreliable (weak) links increase packet drops
  - Reduce delivery rate
  - Increase energy consumption due to retransmissions

Rethink

- Neighbor classification based on link reliability
  - Neighbor blacklist
    - May lead to route disconnection and lower delivery rates, if not careful

Q:

- What is the most energy efficient forwarding strategy?
- How does such strategy draw the line between weak and good links
Distance-Hop Energy Tradeoff

- Minimizing number of hops (by maximizing the geographic distance covered at each hop) may lead to significant energy expenditure due to retransmissions.

- Maximizing per-hop reliability (by forwarding only to close neighbors with good links) may lead to greater energy expenditure due to the need for more transmission hops.

Goal

- Explore distance-hop tradeoff, in order to maximize the energy efficiency of the network during communication events.
The Model

- **Realistic channel model**
  - PRR over a relative small period of time is a good estimator of the channel’s condition
  - \( PRR(d) = (1 - \exp(-\gamma(d)/2*0.64)/2)\rho^8f \)
    - \( \gamma = SNR \)
    - \( \rho = 2 \) (encoding ratio)
    - \( f = \) frame length

- **Modulation**
  - Non-coherent frequency shift keying

- **Encoding**
  - Manchester

- **Metrics**
  - Delivery rate (\( r \))
  - Total number of retransmissions (\( t \))
  - Energy efficient (\( E_{eff} \)) = \( p_{src} * r/kt \)
    - \( K \) is a constant based on \( e_t = e_{tx} + e_{rx} + (n-1)e_{re} \) and conversion factor for energy units
Analytical Model

- **Q:** At each step along the path, how far should a packet be forwarded? (what is the optimal forwarding distance?)

- No network disconnections

- The source-destination path \( (d_{\text{src-dest}}) \) can be described as a chain topology, where nodes are placed every \( \tau \) meters
  - Energy efficiency obtained if a distance \( d \) is traversed at each hop
    - \( Xd = e_{\text{eff}}(d) \)
  - Probability that the optimum forwarding distance is \( d \)
    - \( Qd = f_{xd}(x) \prod_{\forall j \in \psi, j \neq d} Fxj(x) \, dx \)

- Evaluated through numerical computation
Derivation of the chain topology
The Model – ARQ Case

- No a priori constraint on the maximum number of retransmissions \((r=1)\)
- At each hop the expected number of transmissions is \(p_{src}/\text{PRR}(d)\)
  - \(E_{\text{eff}} = \frac{\text{PRR}(d)d}{kd_{src-dest}}\)

- **Results**
  - Best reception neighbor (BR) consumes 100% more than optimal
  - Blacklist neighbors beyond connectivity region consumes 100% or more than optimal
  - Greedy forwarding with a low blacklist threshold consumes 500% more than optimal
Results – ARQ Case

- Probability Mass Function for Various $\tau$
- Relative Energy Cost vs. Forwarding Strategy, with ARQ

Graphs showing the probability mass function and relative energy cost for different forwarding strategies and $\tau$ values.
The Model – No-ARQ Case

- The distance between the source and the destination influences the election of the optimal forwarding distance
  - The longer the distance, the higher the PRR of the chosen links should be

- \( X_d = \)
  - \( PRR(d)^h*(PRR(d)-1)/PRR(d)^h-1, \) if PRR < 1
  - \( 1/p_{src}^h, \) if PRR = 1

- Rule of thumb
  - Best candidate neighbor for forwarding often lies in the transitional region
Results – No-ARQ Case

Probability Mass Function for Various $d_{\text{src-sink}}$:

- $d_{\text{src-sink}} = 200$ m
- $d_{\text{src-sink}} = 400$ m
- $d_{\text{src-sink}} = 800$ m
- $d_{\text{src-sink}} = 1600$ m

Relative Energy Cost vs. Forwarding Strategy, without ARQ:

- $d_{\text{src-sink}} = 200$ m
- $d_{\text{src-sink}} = 400$ m
- $d_{\text{src-sink}} = 800$ m
- $d_{\text{src-sink}} = 1600$ m
Forwarding Strategies for Lossy NW

- **Distance-based**
  - Original greedy
  - Distance-based blacklisting
    - Each node blacklists neighbors that are above a certain distance from itself

- **Reception-based**
  - Absolute blacklisting
    - Node blacklist neighbors that have a reception rate below threshold
  - Relative blacklisting
    - Node blacklist neighbors (that are closer to the destination) a percentage of nodes that have the lowest reception rate

- **Best reception neighbor**
  - Each node forwards to the neighbor with the highest PRR from the neighbors that are closer to the destination

- **Best PRRxdistance**
  - The neighbor with the highest value is chosen
Simulation Results

- Greedy disconnection is an important factor that was not captured in the model
  - Delivery rate is low at low densities because of greedy failures
- Strategies based on reception rate are better than those based only on distance
  - Relative blacklisting reduces disconnection by using the best available links independent of their quality or distance
  - PRRxdistance
    - Has the highest delivery rate
    - More robust and easier to implement
- ARQ becomes more important as the network size increases
Simulation Results

(a) Delivery Rate

(b) Energy Efficiency
Future Work

- Study face (perimeter) routing in lossy networks
- Explore inaccurate locations problem
- Take into account scenarios where link losses vary with time
- Consider MAC contention and their effect in the model and strategies