Balancing Commercial and Defense Technologies

Multihop Routing in Ad Hoc Networks

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Outline

1. Introduction
2. Network Model
3. Outage Probability
4. Routing Protocols
5. Performance Analysis
6. Conclusion

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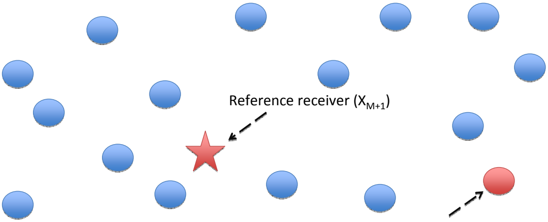
Ad Hoc Networks



- Mobile transmitters are randomly placed in a 2-D finite space.
  - Fixed number of mobiles, placed according to *uniform clustering* model with exclusion zones r_{ex} surrounding each mobile.
- X_0 is the reference transmitter and X_{M+1} is the reference receiver.
- M mobiles $\{X_1, ..., X_M\}$ are potentially relays or sources of interference.
  - Mobile i^{th} is characterized by a *service probability* μ_i.
  - $||X_i - X_j||$ is distance from i^{th} mobile to the j^{th} mobile.
  - Each mobile uses a single omnidirectional antenna.
- The source and the destination communicate through multihop routing.

Typical Network Topology

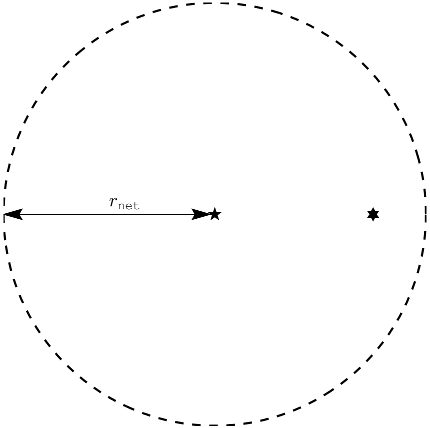


Figure: *Typical network topology. The star at the center of the circle represents the source* X_0*, and the other star represents the destination* X_{M+1}.

- Finite circular area A_{net} with radius r_{net}.
- The reference transmitter is located at the origin.

Typical Network Topology

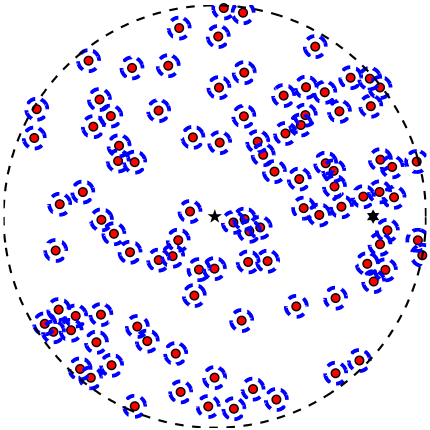


Figure: *Typical network topology. The star at the center of the circle represents the source* X_0*, and the other star represents the destination* X_{M+1}*. In this example, the are* $M = 100$ *other mobiles, each represented by a dot surrounded by its exclusion zone.*

- Finite circular area A_{net} with radius r_{net}.
- The reference transmitter is located at the origin.
- M transmitters are placed uniformly with exclusion zones r_{ex}, such that a minimum separation among them is guaranteed.

Typical Network Topology

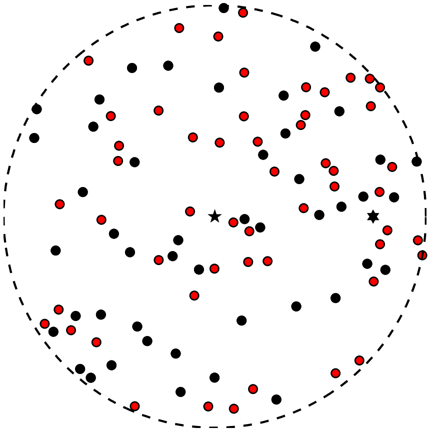


Figure: *Typical network topology. The star at the center of the circle represents the source* X_0*, and the other star represents the destination* X_{M+1}*. In this example, the are* $M = 100$ *other mobiles: black dots are potential relay, while red dots are potential interferes.*

- Finite circular area A_{net} with radius r_{net}.
- The reference transmitter is located at the origin.
- M transmitters are placed uniformly with exclusion zones r_{ex}, such that a minimum separation among them is guaranteed.
- Mobile X_i serves as a relay with service probability μ_i.
- Black dots are potential relays.
- Red dots are potential interferers.

Outline

Received Power

- DS/CDMA-CSMA with collision avoidance is considered as the MAC protocol.
- The despread instantaneous power of X_k received at X_j is

$$\rho_{k,j} = \begin{cases} P_k g_{k,j} 10^{\xi_{k,j}/10} f\left(\|X_k - X_j\|\right) & \text{from the source } X_0 \text{ or a relay} \\ \left(\frac{h}{G}\right) P_k g_{k,j} 10^{\xi_{k,j}/10} f\left(\|X_k - X_j\|\right) & \text{from the } k^{th} \text{ interferer} \end{cases}$$

where
  - P_k is the power transmitted by X_k;
  - $g_{k,j}$ is the power gain due to Nakagami fading;
  - $\xi_{k,j}$ is a *shadowing factor* and $\xi_{k,j} \sim N\left(0, \sigma_s^2\right)$;
  - $f(\cdot)$ is a path-loss function:

$$f(d) = \left(\frac{d}{d_0}\right)^{-\alpha}$$

    - α is the path loss exponent;
    - $d \geq d_0$;
  - h is the chip factor;
  - G is the common spreading factor.

SINR

The performance at mobile X_j when the signal is from the relay X_k is characterized by the signal-to-interference-and-noise ratio (SINR), given by:

$$\gamma_{k,j} = \frac{g_{k,j}\Omega_{k,j}}{\Gamma^{-1} + \frac{h}{G}\sum_{i=1, i\neq k}^{M} I_i g_{i,j}\Omega_{i,j}} \tag{1}$$

where

- Γ is the signal-to-noise ratio (SNR) at a mobile located at unit distance when fading and shadowing are absent;
- $\Omega_{i,j} = \frac{P_i}{P_j} 10^{\xi_{i,j}/10} ||X_i - X_j||^{-\alpha}$ is the normalized power of X_i received by X_j before despreading.
- I_i is a Bernoulli random variable with probability $P[I_i = 1] = p_i$ and $P[I_i = 0] = 1 - p_i$.
  - p_i is the probability that the i^{th} mobile transmits in the same time interval as the desired signal;
  - $\{p_i\}$ can be used to model voice-activity factors, controlled silence or failed link transmissions and the resulting retransmission attempts;
  - $p_i = 0$ if the i^{th} mobile is in service as a potential relay.

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Outage Probability

- An *outage* occurs when the SINR is below a threshold β.
  - β depends on the choice of modulation and coding.
- The *outage probability* of a desired signal from X_k at the mobile X_j conditioned on the network is

$$\epsilon_{k,j} = P\left[\gamma_{k,j} \leq \beta \middle| \mathbf{\Omega}_j\right]. \quad (2)$$

- Substituting (1) into (2), from [8]:

$$\epsilon_{k,j} = 1 - e^{-\frac{\beta_0}{\Gamma}} \sum_{n=0}^{m_{k,j}-1} \left(\frac{\beta_0}{\Gamma}\right)^n \sum_{s=0}^{n} \frac{\Gamma^s}{(n-s)!} \sum_{\substack{\ell_i \geq 0 \\ \sum_{i=0}^{M} \ell_i = k}} \left(\prod_{\substack{i=1 \\ i \neq k}}^{M} G_{\ell_i}(\Psi_i), \right) \quad (3)$$

where $\beta_0 = \beta m_{k,j}/\Omega_0$,

$$G_\ell(\Psi_i) = \frac{\Gamma(\ell + m_{i,j})}{\ell!\Gamma(m_{i,j})} \left(\frac{\Omega_{i,j}}{m_{i,j}}\right)^\ell \left(\frac{\beta_0 h \Omega_{i,j}}{G m_{i,j}} + 1\right)^{-m_{i,j}-\ell}. \quad (4)$$

[8] D. Torrieri and M.C. Valenti, "The outage probability of a finite ad hoc network in Nakagami fading", *IEEE Trans. Commun.*, Nov. 2012.

Distance-Dependent Fading Model

- In (3) non-identical Nakagami-m parameters can be chosen to characterize the fading from the mobile X_i to the mobile X_j and a *distance-depending fading* model can be adopted:

$$m_{i,j} = \begin{cases} 3 & \text{if } ||X_i - X_j|| \leq r_{\mathsf{f}}/2 \\ 2 & \text{if } r_{\mathsf{f}}/2 < ||X_i - X_j| \leq r_{\mathsf{f}} \\ 1 & \text{if } ||X_i - X_j| > r_{\mathsf{f}} \end{cases} \tag{5}$$

  where r_{f} is the *line-of-sight radius*.

- The distance-dependent-fading model characterizes the situation where a mobile close to the base station is in the line-of-sight (LOS), while mobiles farther away tend to be non-LOS.

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Candidate Links

- A *distance criterion* is used to exclude links in one of possible paths from X_0 to X_{M+1}. In particular, a link from mobile X_a to mobile X_b is excluded if
$$||X_b - X_{M+1}|| > ||X_a - X_{M+1}||.$$
  - Links that have not been excluded are called *included* links.
  - *Included* links always reduce the remaining distance to the destination.
- For each included link i, the outage probability ϵ_i is determined using (3).
- A Monte Carlo simulation uses the outage probabilities as failure probabilities to determine which of these links provides a successful transmission after B or fewer transmission attempts.
- Each included link that passes the latter test is called a *candidate link*, from which the *candidate paths* can be formed.

Transmission Delay

- The *delay of candidate link* i is
$$T_i = N_i T + (N_i - 1)T_e \qquad (6)$$
where
  - T is the *delay of a transmission over a link*;
  - T_e is the *excess delay* caused by a retransmission;
  - N_i is the number of transmission attempts required for successful transmission, where $N_i \leq B$.
- The *delay* $T_{s,t}$ of a path from X_0 to X_{M+1} for network topology t and simulation trial s is
$$T_{s,t} = \sum_{i \in \mathcal{L}_{s,t}} [N_i T + (N_i - 1)T_e] \qquad (7)$$
where
  - $\mathcal{L}_{s,t}$ is the set of candidate links constituting the path.
- For each topology t, (7) is evaluated for K_t trials.
- $\{T_{s,t}\}$ for topology t are sorted in ascending order of delay.
- If there is a routing failure, then $1/T_{s,t} = 0$.

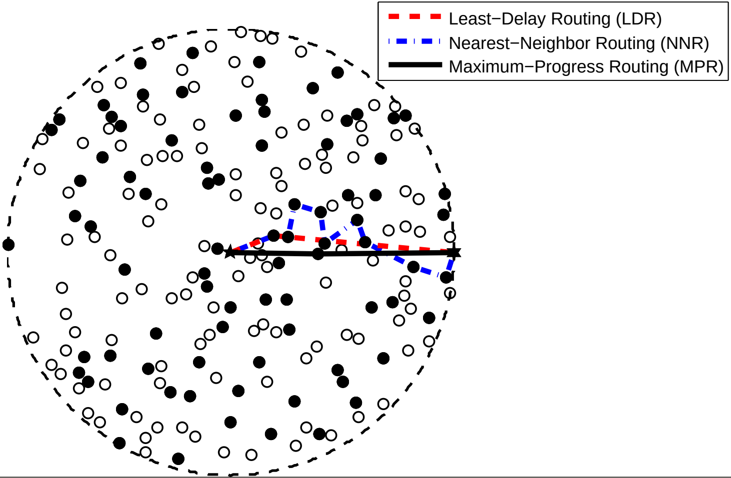
Routing Protocols

1. *Least-delay* routing (LDR) protocol:
   - The candidate path with the smallest delay from X_0 to X_{M+1} is selected as the *least-delay path* from X_0 to X_{M+1}.
   - This path is determined by using the *Djikstra algorithm* with the candidate links and the cost of each link equal to the delay of the link.
2. *Nearest-neighbor* routing (NNR) protocol:
   - Nearest-neighbor routing builds the *nearest-neighbor path* by choosing the closest relay that lies at the end of a candidate link as the next one in the path from X_0 to X_{M+1}.
3. *Maximum-progress* routing (MPR) protocol:
   - Maximum-progress routing constructs the *maximum-progress path* by choosing the next relay on the path as the one that lies at the end of a candidate link and minimizes the remaining distance to the destination.

- For all the three protocols, if there is no set of candidate links that allow a path from X_0 to X_{M+1}, then a *routing failure* occurs.

Example: Routing Protocols

1. *Least-delay* routing (LDR) protocol;
2. *Nearest-neighbor* routing (NNR) protocol;
3. *Maximum-progress* routing (MPR) protocol.



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Performance Metrics

- The *path reliability* within topology t is
$$R_t = 1 - \frac{F_t}{K_t}. \tag{8}$$
where
  - F_t are the routing failures for topology t;
  - K_t are the simulation trials.
- The *conditional average delay* from X_0 to X_{M+1} is
$$D_t = \frac{1}{K_t - F_t} \sum_{s=1}^{K_t - F_t} T_{s,t}. \tag{9}$$
- The *normalized area spectral efficiency* for the K_t trials of topology t is
$$\mathcal{A}_t = \frac{\lambda}{K_t} \sum_{s=1}^{K_t} \frac{1}{T_{s,t}} \tag{10}$$
- After computing R_t, D_t and $\mathcal{A}_t$ for Υ network topologies, their *spatial averages* can be computed as following:
$$\overline{R} = \frac{1}{\Upsilon} \sum_{t=1}^{\Upsilon} R_t, \quad \overline{D} = \frac{1}{\Upsilon} \sum_{t=1}^{\Upsilon} D_t, \quad \overline{\mathcal{A}} = \frac{1}{\Upsilon} \sum_{t=1}^{\Upsilon} \mathcal{A}_t. \tag{11}$$

Simulation Methodology

- The simulation can be divided into three levels:
  - *Level 1: Topology.* The source mobile is placed at the origin, and the destination mobile is placed a distance $||X_0 - X_{M+1}||$ from it. The other M mobiles are randomly placed according to the uniform clustering process.
  - *Level 2: Service Model.* Each of the M mobiles is marked as available as a relay with probability μ_i.
  - *Level 3: Link-Level Simulation.* The outage probability at each potential relay or destination is computed by using (3), where each mobile that is not a potential relay is a source of interference with probability p_i. By simulating outages, the candidate links are determined, and the required number of transmissions is determined for each of these links.
- During each simulation trial, the least-delay, nearest-neighbor, and maximum-progress routes are identified.
- For each topology and after K_t trials, (8-10) are computed.

Path Reliability Vs Distance

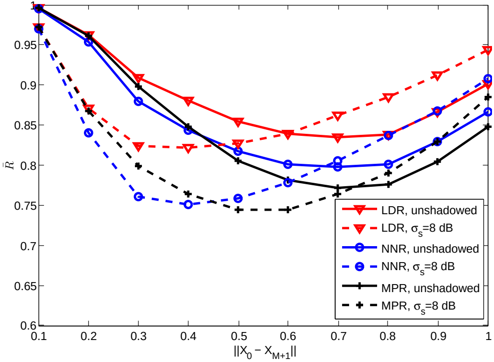

Figure: *Path reliability as a function of the distance between source and destination.*

Example:

- $M = 200$;
- $T = T_e = 1$;
- $\mu_i = 0.3$;
- $p_i = 0.4$;
- $r_{net} = 1$;
- $r_{ex} = 0.05$;
- $r_f = 0.2$;
- $\alpha = 3.5$;
- $\Gamma = 10$ dB;
- $G/h = 48$;
- $\sigma_s = 8$ dB;
- $\beta = 3$ dB;
- $B = 4$.

Conditional Average Delay Vs Distance

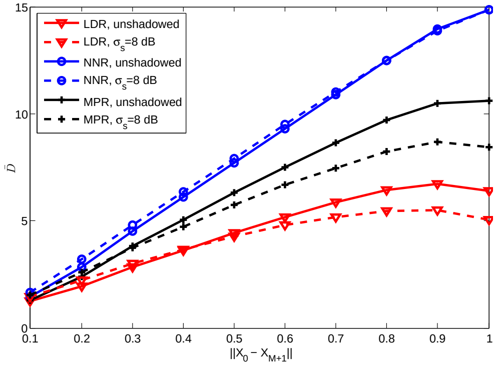

Figure: *Conditional average delay as a function of the distance between source and destination.*

Example:

- $M = 200$;
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Area Spectral Efficiency Vs Distance

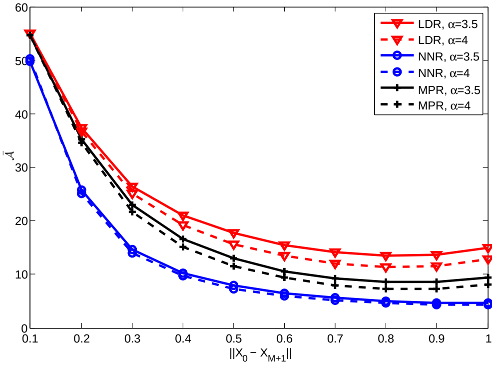

Figure: *Normalized area spectral efficiency as a function of the distance between source and destination.*

Example:

- $M = 200$;
- $T = T_e = 1$;
- $\mu_i = 0.3$;
- $p_i = 0.4$;
- $r_{net} = 1$;
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- $\beta = 3$ dB;
- $B = 4$.

Area Spectral Efficiency Vs Retransmissions

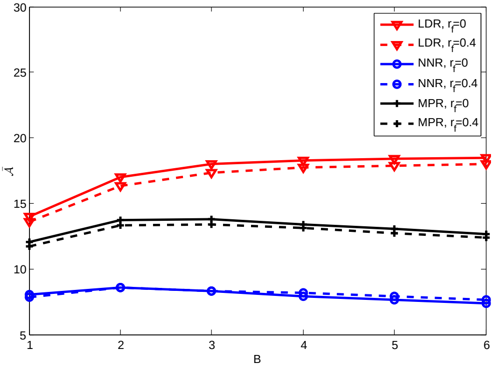

Figure: *Normalized area spectral efficiency as a function of the number of allowed transmissions.*

Example:

- $M = 200$;
- $T = T_e = 1$;
- $\mu_i = 0.3$;
- $p_i = 0.4$;
- $r_{net} = 1$;
- $r_{ex} = 0.05$;
- $\alpha = 3.5$;
- $\Gamma = 10$ dB;
- $G/h = 48$;
- $\sigma_s = 8$ dB;
- $\beta = 3$ dB;
- $\delta\left(X_0, X_{M+1}\right) = 0.5$

Area Spectral Efficiency Vs Spreading Factor

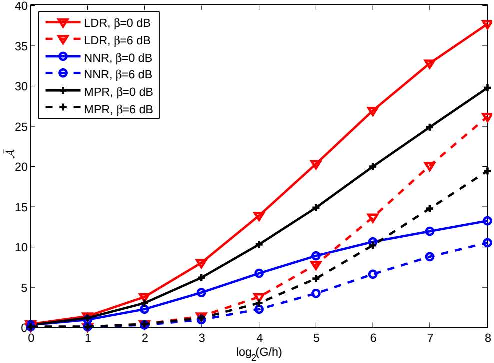

Figure: *Normalized area spectral efficiency as a function of the spreading factor.*

Example:

- $M = 200$;
- $T = T_e = 1$;
- $\mu_i = 0.3$;
- $p_i = 0.4$;
- $r_{net} = 1$;
- $r_{ex} = 0.05$;
- $\alpha = 3.5$;
- $\Gamma = 10$ dB;
- $\sigma_s = 8$ dB;
- $\delta(X_0, X_{M+1}) = 0.5$
- $B = 4$

Path Reliability Vs Contention Density

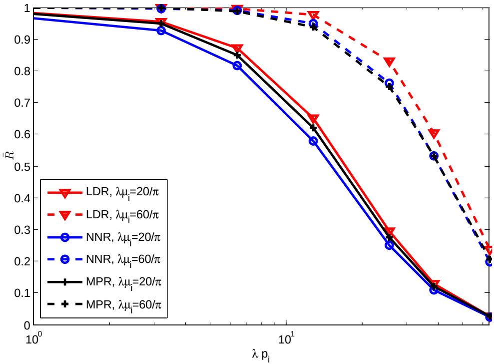

Figure: *Path reliability as a function of contention density.*

Example:

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- $r_f = 0.2$
- $\alpha = 3.5$;
- $\Gamma = 10$ dB;
- $G/h = 48$;
- $\sigma_s = 8$ dB;
- $\beta = 3$ dB;
- $\delta(X_0, X_{M+1}) = 0.5$;
- $B = 4$.

Outline

Conclusions

- The new approach for modeling and analyzing a multihop routing has the following benefits:
  - The network is finite as well the number of mobiles.
  - Distinct links do not necessarily experience identically distributed fading.
  - Source-destination pairs are not assumed to be stochastically equivalent.
  - There is no assumption of independent path selection, path success probabilities, or link (hop) success probabilities.
  - The shadowing over the link from one mobile to another can be modeled individually, as required by the local terrain.
  - The analysis accounts for the thermal noise, which is an important consideration when the mobile density, and hence the interference, is moderate or low.
- The new analysis is combined with a simulation to compare three routing protocols.
- The tradeoffs among the path reliabilities, average delays, and area spectral efficiencies of these three routing protocols and the effects of various parameters have been shown.

Thank You