Throughput-Delay-Reliability Tradeoffs in Multihop Networks with Random Access

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Overview

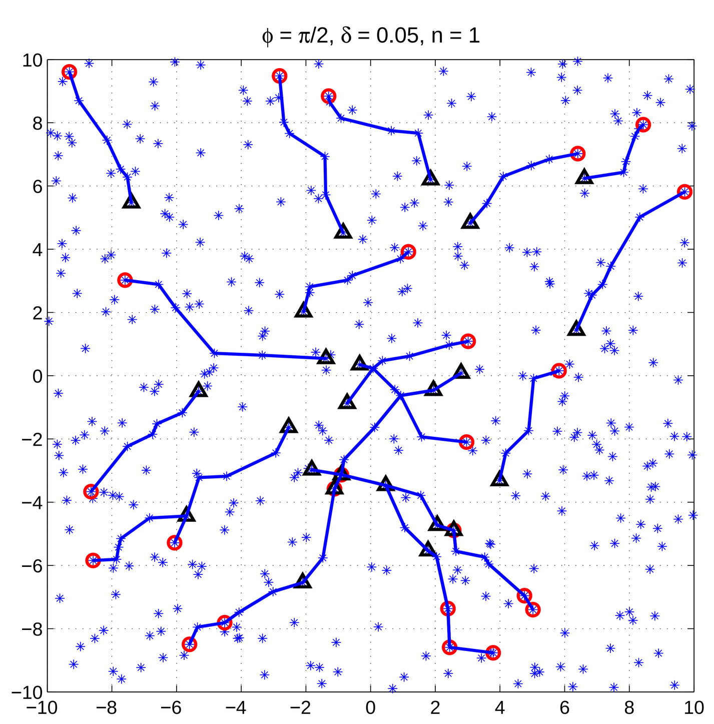
- Throughput-delay-reliability (TDR) tradeoffs exist in multihop networks.
- In scenarios where reliable delivery is not critical, one can have the nodes forcibly drop a small fraction of packets.

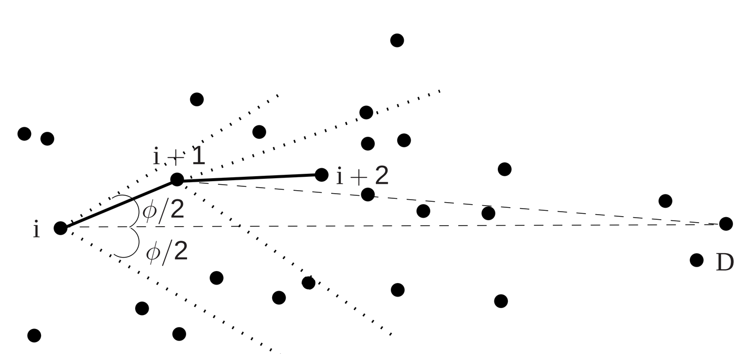
Limitations in Prior work:

- Analyzed single-hop networks [Abouei '09].
- Neglected dependence of packet dropping on success events [Xie '05].
- Assumed all nodes to be backlogged [Vaze '10].

System Model

- Several flows, each occurring over an infinite duration of time.
- Source nodes: PPP (δ); relays and destinations: PPP ($1-\delta$)



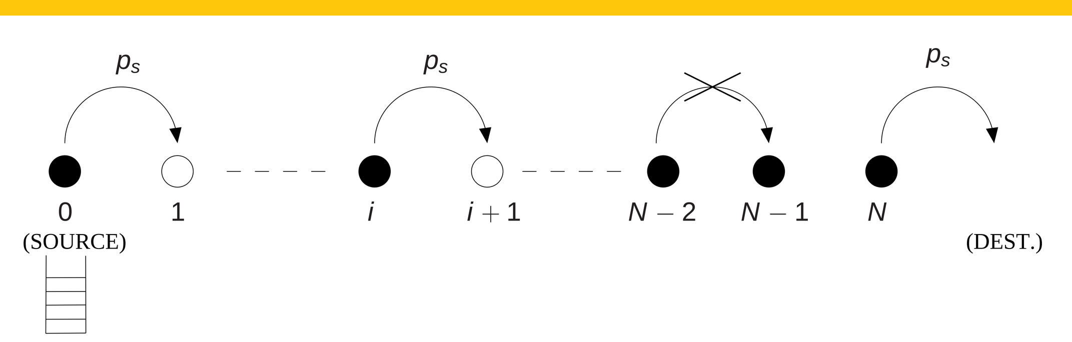


- Transmission success events are dictated by the SINR model.

$$p_s = \Pr\left(\frac{G_{xy}\|x-y\|^{-\gamma}}{N_0 + I_{\Phi\setminus\{x\}}(y)} > \Theta\right).$$

- **A revised buffering and transmission policy:**
  - All the buffering is done at the source; relays have buffer sizes of unity.
  - Nodes do not accept incoming packets if they already have one.
  - Packets are retransmitted until they are successfully received.
- **MAC Scheme**: Slotted ALOHA with contention parameter q.

A Typical Flow



$\tau_i[t] \in \{0, 1\}$: *configuration* of site i, $0 \le i \le N$ in time slot t.

Performance Metrics: TDR

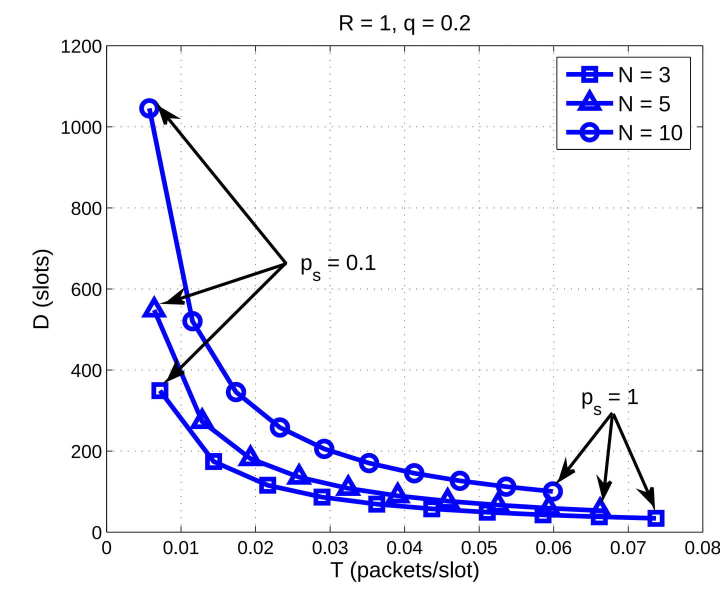
- The per-flow **throughput** T, is defined as the average number of packets successfully delivered (to the destination) in unit time, along a typical flow in the network.
- The **mean end-to-end delay**, D, is defined as the average number of time slots it takes for the packet at the head of the source node to successfully hop to the destination.
- The **end-to-end reliability** R is defined as the fraction of packets generated at the source that are eventually delivered.

The Regime $R = 1$

$$T = \frac{qp_s B(N)}{B(N+1) + qp_s B(N)}; \quad D = (1 + N/2)/T.$$

where $B(0) = 1$, and

$$B(k) = \sum_{j=0}^{k-1} \frac{1}{k}\binom{k}{j}\binom{k}{j+1}(1-qp_s)^j, \quad k > 0.$$



For each value of N, the TD curve is a hyperbola.

The Regime $R < 1$

- When $R = 1$, D and T performances are poor at small p_s.
- Nodes can choose to drop a small fraction of packets ($R < 1$).
- We consider the case of stochastic dropping w.p. ξ.

System Evolution:

- The following events affect τ_i:

a) Node $i-1$ transmits its packet to node i.

b) Node i transmits its packet to node $i+1$.

c) Node i drops its packet.

- Employing mean-field theory, we obtain at steady state, $\mathbb{E}\lim_{t\to\infty}\Delta\tau_i[t] = 0$ for $1 \le i \le N$, i.e.,

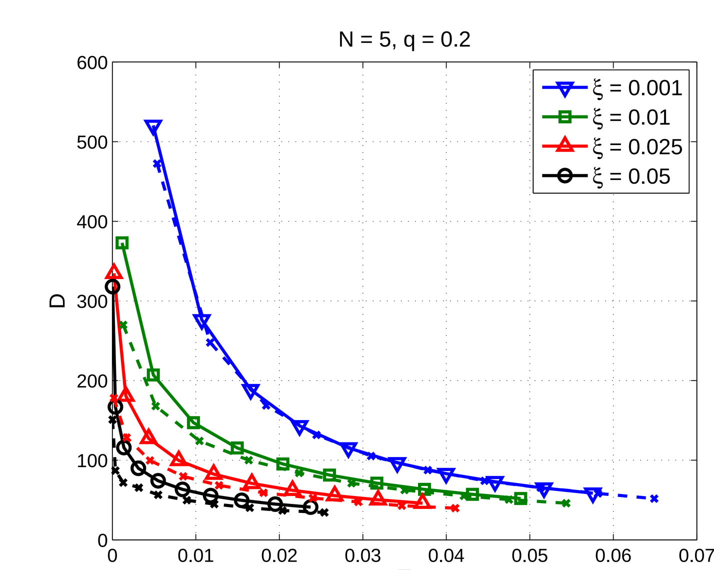
$$p_s(1-\xi)q\big[\underbrace{\mathbb{E}\tau_{i-1}(1-\mathbb{E}\tau_i)}_{a)} - \underbrace{\mathbb{E}\tau_i(1-\mathbb{E}\tau_{i+1})}_{b)}\big] - \underbrace{\xi\mathbb{E}\tau_i}_{c)} = 0.$$

- The steady state occupancies $\mathbb{E}\tau_i$ may be obtained by numerically solving these N non-linear equations.

$$T = qp_s\mathbb{E}\tau_N; \quad D = \sum_{i=0}^{N} s_i^{-1}; \quad R = \prod_{i=0}^{N}\frac{s_i(1-\xi)}{s_i + \xi - s_i\xi}.$$

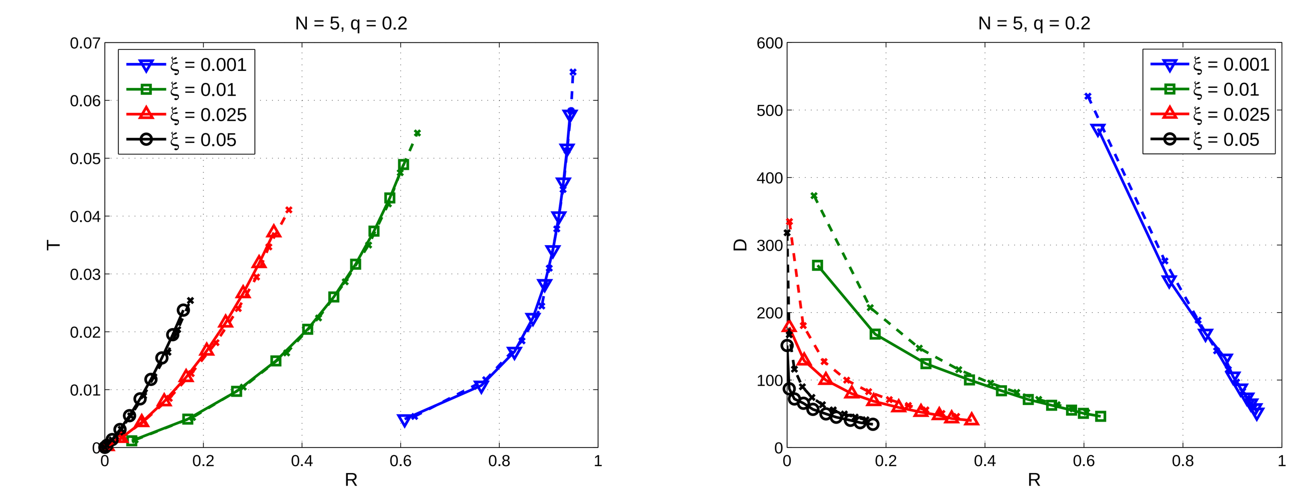
where $s_i = qp_s(1 - \mathbb{E}\tau_{i+1})$.

The Noise-Limited Regime



Increasing ξ helps reduce the end-to-end delay significantly.

The Regime $R < 1$

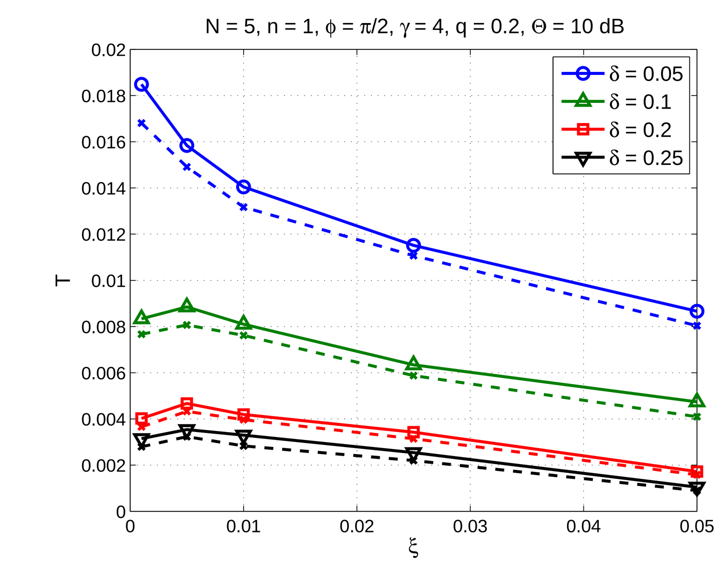


The throughput and reliability performances worsen too.

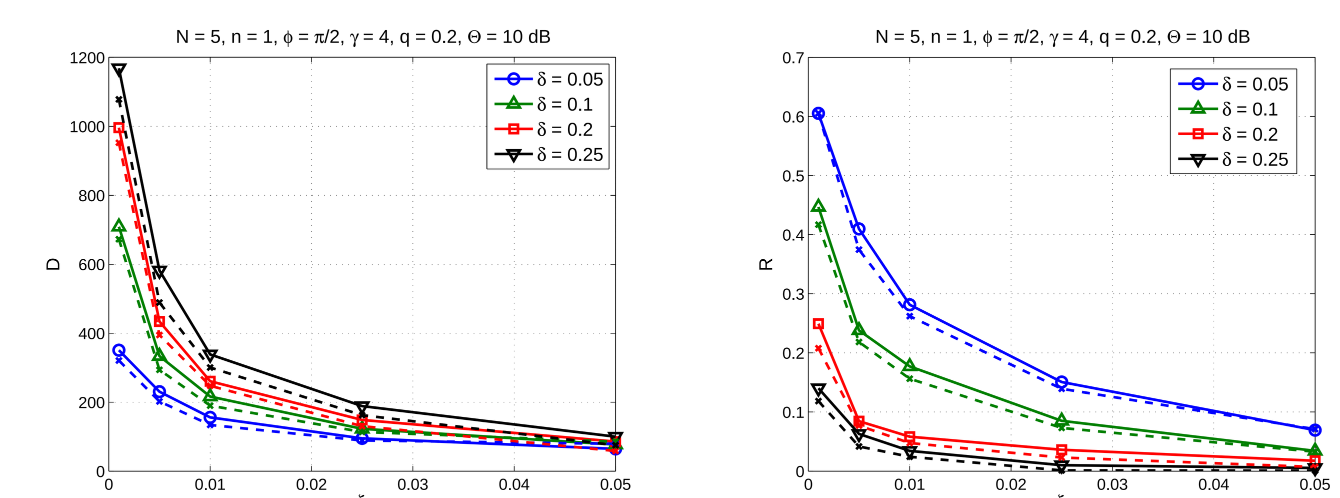
The Interference-Limited Regime

- The average number of potential interferers in each flow is $1 + \sum_{i=1}^{N}\mathbb{E}\tau_i$.
  - The set of interferers (approximately) forms a PPP with density $\lambda_I = \delta q\left(1 + \sum_{i=1}^{N}\mathbb{E}\tau_i\right)$.
- The probability of a successful transmission for a typical link is

$$p_s \gtrsim \left(\frac{(1-\delta)\phi}{(1-\delta)\phi + 2\delta q\left(1+\sum_{i=1}^{N}\mathbb{E}\tau_i\right)c}\right)^n.$$



- When δ is small, increasing the packet dropping probability ξ reduces the system throughput.
- As δ gets larger, dropping a few packets helps mitigate the interference, and the throughput across a typical flow improves.



With increasing ξ or decreasing δ, the mean end-to-end delay decreases; the reliability also suffers.

Conclusions

- In the noise-limited regime, dropping a small fraction of packets in the network leads to a smaller end-to-end delay at the cost of reduced throughput.
- In the interference-limited scenario, dropping a few packets in the network can help mitigate the interference in the network leading to an increased throughput.