Routing for Real-time Constrained Packet Flows

Neda Petreska, Christian Dombrowski, James Gross
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RWTH AACHEN UNIVERSITY

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Machine-to-Machine Communication & QoS

- **Traditionally, wireless networks are considered for:**
  - Soft real-time applications
  - Best-effort applications

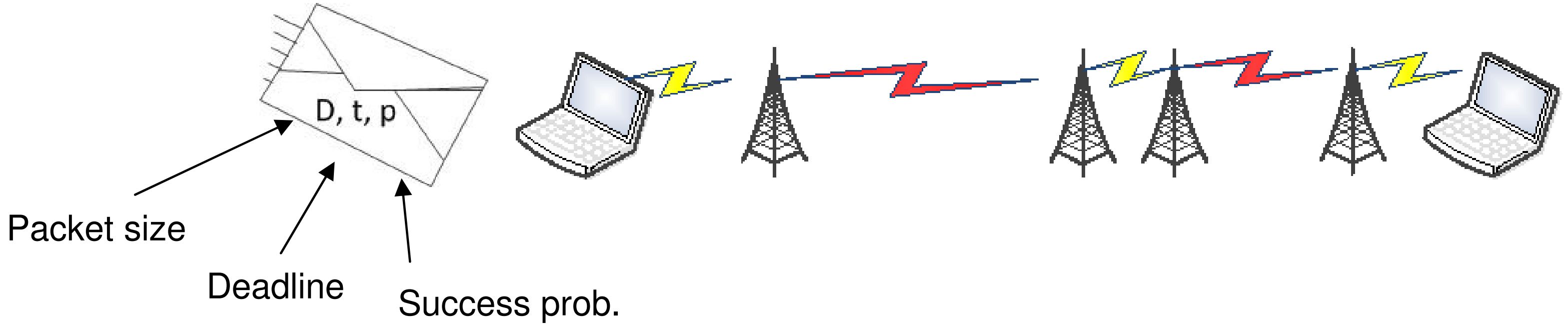
- **Recent interest in Machine-to-Machine (M2M) communication**
  - Part of the ‚Internet of Things‘ vision

- **Several applications in M2M have much tougher QoS constraints (‚hard real-time‘):**
  - Control applications
  - Industrial automation
  - Context-aware distributed systems
  - Cyber-physical systems

- **Research focus in this work:**
  - Can we meet such QoS requirements at all?
  - Which models and algorithms can be used?

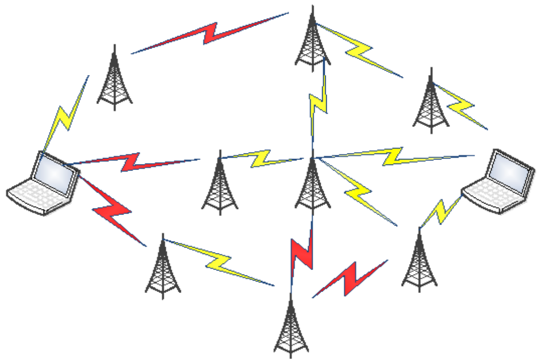
Research Challenges & Contributions

- **Consider transmission of a flow over a given multi-hop path:**



  - Can the given path accept the flow?
  - What are the optimal resource allocations along the path (power and time)?

- **Consider an arbitrary multi-hop network between two machines:**
  - Can the network accept the flow?
  - What is the most efficient forwarding path for the flow?



General System Model

- **Stationary, multi-hop network**
- **Deterministic medium access, fixed time slots**
- **Application characteristics**
  - Packets with size D, end-to-end deadline t, success probability p
  - Packet interarrival time much bigger than end-to-end deadline
- **Link model**
  - Rayleigh fading channel
  - No interference from other nodes
  - Only average CSI at transmitter
  - Shannon capacity as power-rate function
  - Nodes can set transmit power within a certain range $[0; P_i^{max}]$
- **Marginal queuing behavior**

Basic Relationships

- **Each link is characterized by:**
  - Probability for successful transmission

$$p_i : \prod_{i=1}^{n} p_i \geq p$$

  - Available time amount for forwarding the packet

$$t_i : \sum_{i=1}^{n} t_i \leq t$$

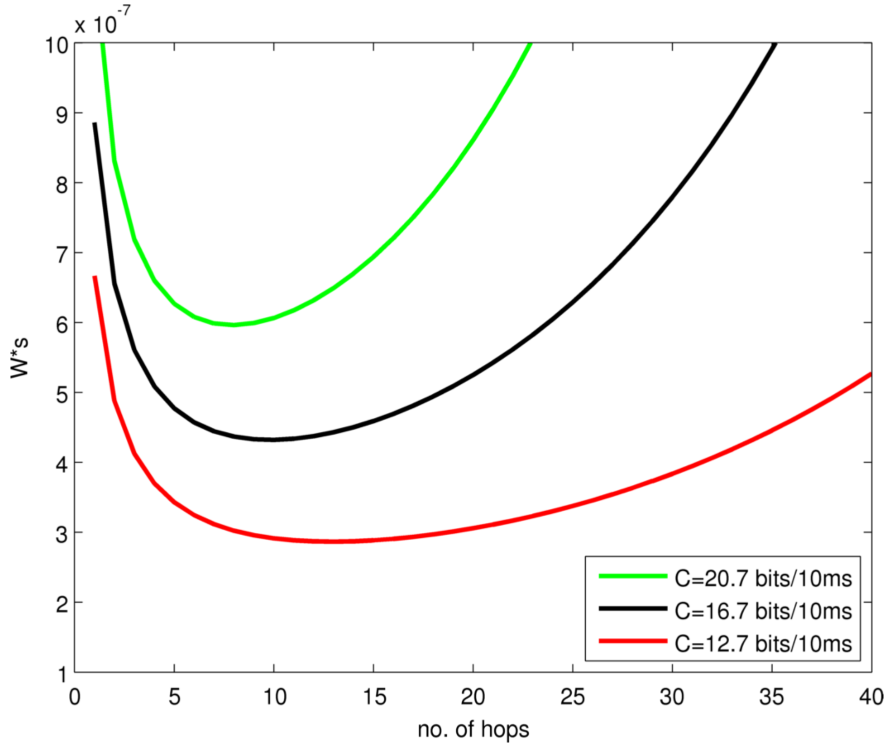
- **Transmit power needed for a direct transmission:**

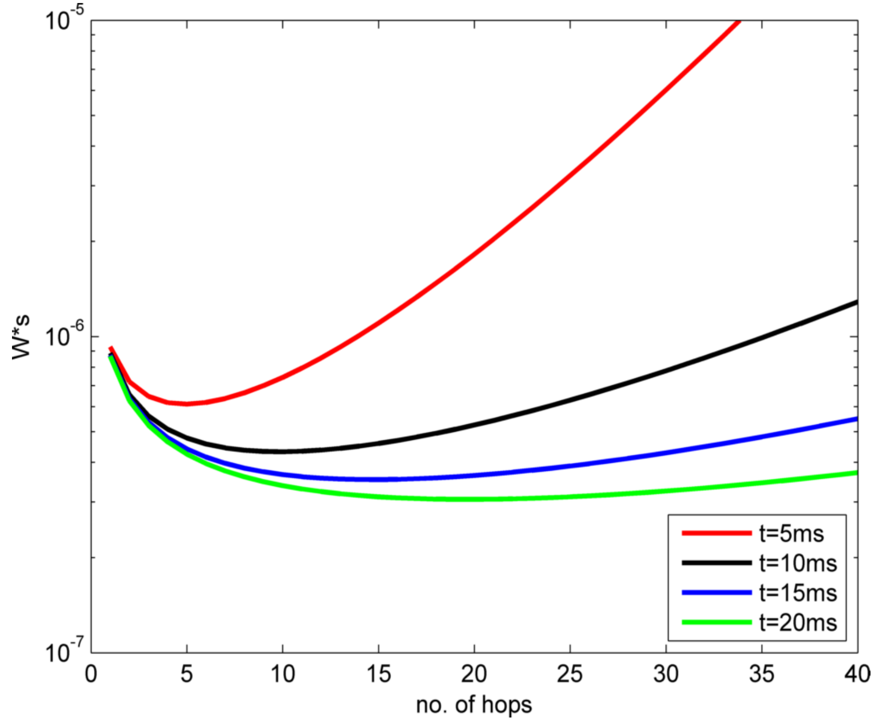
$$P_{tx} = \frac{B\mathrm{N}_0}{h_{\mathrm{PL}}^2 \ln(p)}(1 - 2^{\frac{D}{tB}})$$

- **Total end-to-end energy consumption:**

$$E(n) = \sum_{i=1}^{n} \frac{B\mathrm{N}_0}{h_i^2 \ln(p_i)}(1 - 2^{\frac{D}{t_i B}})t_i$$

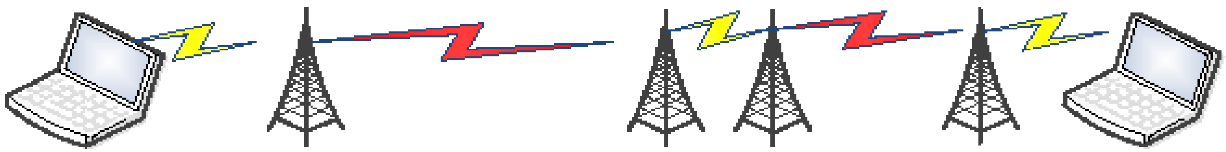
Graphical Representation of the Energy Behaviour





- Convex behaviour in case of equally distanced relays
- Left: Bigger demanded data rate → bigger energy consumption
- Right: Bigger end-to-end delay → smaller energy consumption

Optimal Power Distribution



- **Fixed time slot per hop** $t_i = \frac{t}{n}$
- **Minimum transmit power theorem:**
  - The transmit power that each node on a path with n randomly spaced relays has to use in order to forward a packet of size D with a QoS parameters t and p is defined by

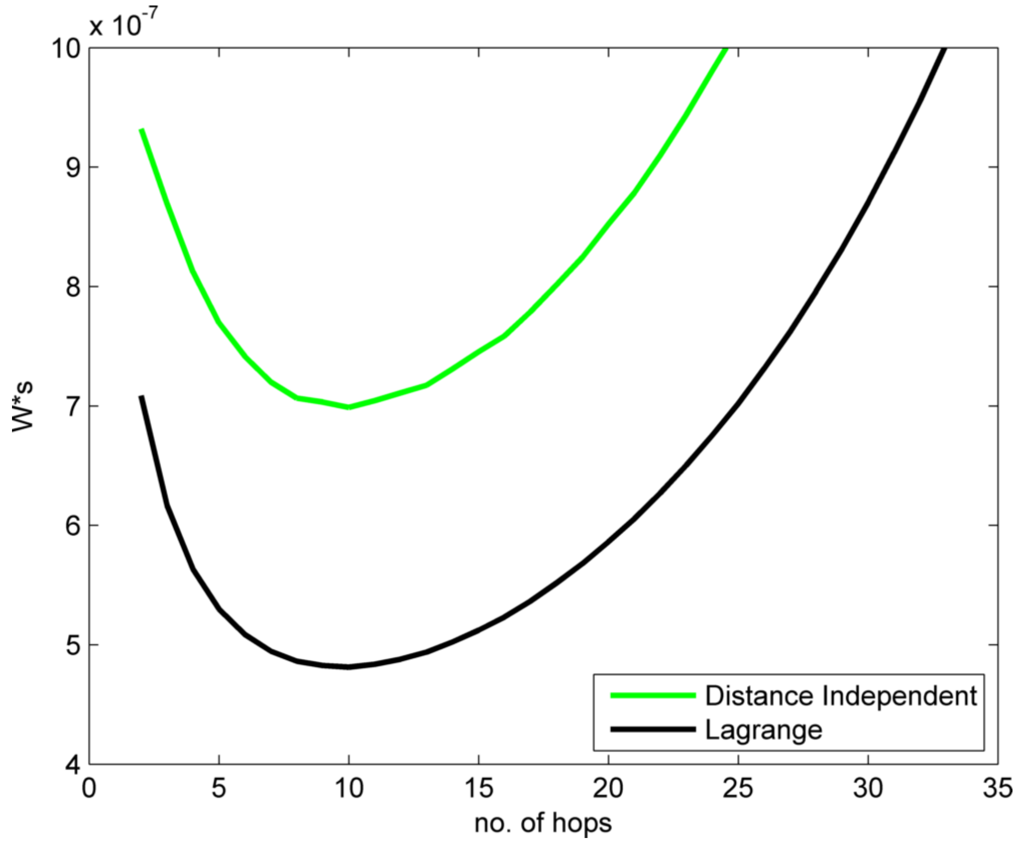
$$P_i = \frac{B\mathrm{N}_0}{\sqrt{h_i^2 \ln(p)}} \sum_{j=1}^{n} \frac{1}{\sqrt{h_j^2}} \left(1 - 2^{\frac{nD}{tB}}\right)$$

- **Probability assignment strategies**
  - Distance Independent

$$p_i = \sqrt[n]{p}$$

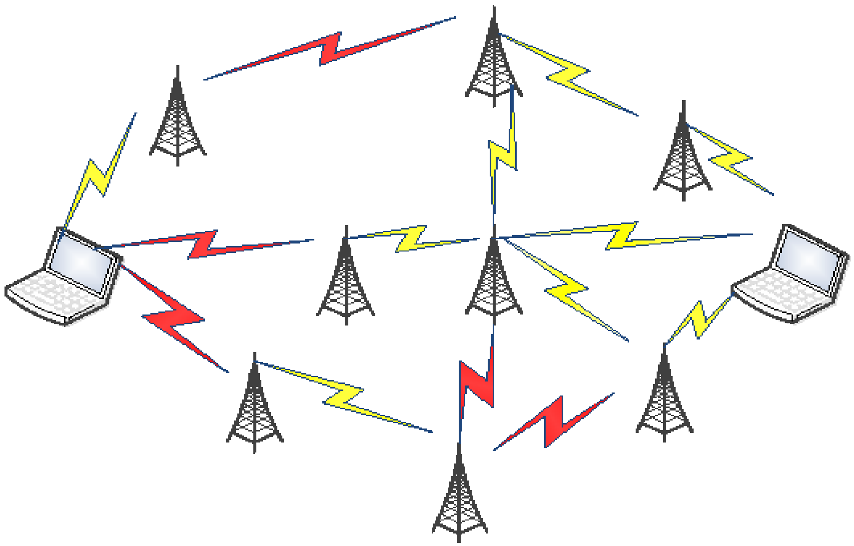
  - Lagrange

$$p_i = \exp\left(\frac{1}{\sqrt{h_i^2}\sum_{j=1}^{n}\frac{1}{\sqrt{h_j^2}}}\ln(p)\right)$$



- **Results derived by means of simulation and averaged over more than 10000 replications**

Routing Scenario



- Find the most energy-efficient path that satisfies the end-to-end requirements for a source-destination pair
- Traditional routing schemes fail to locate the minimal energy path
- Modify Floyd-Warshall algorithm – additionally store the number of hops between the source and the destination
- Algorithm's complexity $\Omega(N|V|^3)$, where $N = \lceil \frac{t}{t_{hop}} \rceil$

Routing Algorithm

- **Pseudo code:**
  - Distribute network information among nodes
  - Define $N = \lceil \frac{t}{t_{hop}} \rceil$
  - Define link weights as $\frac{1}{\sqrt{h_i^2}}$
  - For $n = 1..N$ do
    - Find minimal energy path with exactly n hops (modified Floyd-Warshall Algorithm) according to:

$$E = \frac{1}{n}\frac{B\mathrm{N}_0 t}{\ln(p)}\left(1 - 2^{\frac{nD}{tB}}\right)\left(\sum_{i=1}^{n}\frac{1}{\sqrt{h_i^2}}\right)^2$$

    - If n-hop shortest path exists:
      - Compute associated energy

      else

      - Set energy to $+\infty$
  - Find the minimal energy path from set with at most N elements

Concluding Thoughts

- **Initial study on providing hard real-time QoS in multi-hop networks for M2M communication**

- **Contributions:**
  - Optimal power allocation along a path

    ➔ Determines if a given path can provide required QoS at all
  - Efficient routing algorithm for determining most efficient path in an arbitrary multi-hop network

    ➔ Can the network provide the QoS requirements at all?

Future Work

- **Per-hop queuing behavour**
  - Stochastic Network Calculus methods
- **Self-interference**
  - Increased energy consumption
- **Multipath routing and back-up paths**
  - Find n distinct, feasible routes with an optimal resource allocation
  - Intermediate back-up routes
- **Currently working on a prototype**