Universal Routing in Multi Hop Radio Networks

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Synopsis

- dynamic routing in multi-hop radio networks in the framework of adversarial queuing
- cross-layer interactions of three components of routing:
  - transmission policies for medium-access control,
  - scheduling policies on the network layer, and
  - hearing-control mechanisms
- a model of adversarial queuing in radio networks
  - transmission policies are delegated to oracles
  - adversaries control packet injection
- adaptations of the notion of universal stability
- investigate which scheduling policies are universally stable and which are not
adaptations of the notion of universal stability

to investigate which scheduling policies are universally stable and which are not

historical note: the notion of universal stability for wired networks was introduced by Andrews et al. (JACM, 2001) and systematically studied by Alvarez et al. (SICOMP, 2004) in the context of seminal work on adversarial queuing
Radio networks

- what are radio networks:
  - arbitrary topology of a simple connected graph
  - synchronous execution of a communication algorithm (partitioned into rounds)
  - when two messages arrive at a node $v$ transmitted by its neighbor such that their receipt overlaps in time then they interfere with each other and none can be heard by $v$
  - when only one neighbor of a node $v$ transmits a message in a round then $v$ hears this message.
Each node uses a queue to temporarily store packets to be transmitted.

The buffer space at a node can store an arbitrarily large number of packets.

No packet is discarded until its delivery to the destination.

A packet message carries a header which includes the packet’s itinerary, so there is no need of routing tables.

A routing algorithm has the following three components:
- scheduling policy
- transmission policy
- hearing control
Hearing control

It is a mechanism to coordinate scheduling with transmissions.

We consider two main alternative approaches:

- The proactive hearing control: when a node wants to transmit in a round, it first obtains a list of neighbors that will hear the message in the round (a short trial transmission $\rightarrow$ acknowledge when heard)

- The reactive hearing control: immediately after a transmission, a sender is notified if the intended recipient node has heard the message (acknowledgement from the targeted neighbor)

A hearing control implemented by control messages of small size and negligible time
A scheduling policy

A rule to select one packet from a group of packets at a node.

Popular queueing policies: Furthest-From-Source (FFS), Furthest-To-Go (FTG), Nearest-To-Source (NTS), Nearest-To-Go (NTG), Shortest-In-System (SIS), and Longest-In-System (LIS).

A scheduling policy $S$ is coordinated with a hearing control.

- $S_{pre}$ denotes $S$ working with a proactive hearing control: $S$ selects a packet to transmit from those parked in the queue for whom one of the neighbors that will hear a message in their next stop on their path to the destination.

- $S_{post}$ denotes $S$ working with a reactive hearing control: $S$ selects a packet to transmit from all parked in the queue.
To indicate to a node whether to transmit in a round or rather to pause in this round

- Goal: to facilitate packet movement by avoiding collisions of packets transmitted by different neighbors of nodes.
- We abstract from implementing transmission policies, but delegate such a task to a *transmission oracle* that indicates to each node whether or not to transmit in a round.
- Motivation I: we want to investigate stability of scheduling policies not transmission policies.
- Motivation II: transmission oracle allows to have a hearing rate to be aligned with rate of injecting packets.
An integer $h_e > 0$ is a *hearing latency of link* $e$ if link $e$ allows to successfully transmit at least one packet each $h_e$ consecutive rounds.

A transmission oracle *provides a link latency* $h$ when hearing latencies of all links are upper bounded by $h$.

$\mathcal{T}_h^{\text{link}}$, or simply by $\mathcal{T}_h$, denotes the class of transmission oracles that provide a link hearing latency of $h$.

If $h$ is a latency of hearing then $1/h$ is the resulting rate of hearing.

Rates of hearing and injection need to be aligned.
An integer $h_v > 0$ is a **hearing latency of node $v$** if node $v$ is guaranteed to be able to successfully transmit, using any link, at least one packet each $h_v$ consecutive rounds.

A transmission oracle *provides a node latency $h$ when hearing latencies of all nodes are upper bounded by $h$.*

$T_{h}^{\text{node}}$ denotes the class of transmission oracles that provide a node hearing latency of $h$.

Observe that if $T \in T_{h}^{\text{node}}$ then $T \in T_{h}^{\text{link}}$. 
Packets are injected by adversaries along with paths to traverse.

- An adversary is determined by a pair of numbers \((b, r)\), called the type of the adversary, where burstiness \(b\) is a positive integer and injection rate \(r\) satisfies \(0 \leq r < 1\). We denote by \(A(b, r)\) an adversary of type \((b, r)\).

- Let \(I(\tau, v)\) represent the number of packets that the adversary injects during time interval \(\tau\) and has node \(v\) on its path. An \(A(b, r)\) adversary is constrained such that the inequality \(I(\tau, v) \leq r \cdot |\tau| + b\) has to hold for any \(\tau\) and \(v\).
Stability

- \( P(\mathcal{T}, S) \): the routing protocol based on a transmission oracle \( \mathcal{T} \) and a scheduling policy \( S \)
- Stability of \( P(\mathcal{T}, S) \) means bounded queues in the course of an unbounded execution
- \( P(\mathcal{T}, S) \) is *stable against adversary* \( \mathcal{A} \) if each execution of \( P(\mathcal{T}, S) \) against \( \mathcal{A} \) in any network \( G \) is stable.

Observe that for a protocol using transmission policy \( \mathcal{T} \) to be stable against an adversary \( \mathcal{A} \), the injection rate of this adversary cannot be greater than the node latency provided by \( \mathcal{T} \) for any node.

- A scheduling policy \( S \) with \( \mathcal{T}_h \) is *stable against adversary* \( \mathcal{A} \) if for any \( \mathcal{T} \in \mathcal{T}_h \), protocol \( P(\mathcal{T}, S) \) is stable against adversary \( \mathcal{A} \).
A scheduling policy $S$ is \textit{link universally stable} when $S$ with $T^\text{link}_h$ is stable for any adversary whose injection rate is strictly smaller than $1/h$, for any $h \geq 1$.

A scheduling policy $S$ is \textit{node universally stable} when $S$ with $T^\text{node}_h$ is stable for any adversary whose injection rate is strictly smaller than $1/h$, for any $h \geq 1$.

A scheduling policy that is not universally stable is called unstable, which comes in two variants as \textit{link unstable} and \textit{node unstable}, respectively.
The Shortest-In-System (SIS) scheduling policy gives priority to the packet that has been in the system the shortest, with ties broken arbitrarily.

Notation: $T_h^{\text{link}}$ means: link latency at most $h$

**Theorem**

The scheduling policy $\text{SIS}_{\text{pre}}$ is link universally stable. If a transmission policy is in the class $T_h^{\text{link}}$ then no queue contains more than $k_d$ packets, where $d$ denotes the length of the longest simple directed path in the graph, and no packet spends more than $\sum_{i=1}^{d} \left( \frac{k_i + b}{1 - rh} \right) \cdot h$ rounds in the system.
The *Longest-In-System* (LIS) scheduling policy gives priority to a packet that has been in the system the longest, with ties broken arbitrarily.

**Theorem**

The scheduling policy $LIS_{\pre} \text{ is link universally stable.}$

If a transmission policy is in the class $T_h$ then no queue contains more than $r \cdot ((b + r) \cdot h \cdot (d - 1) + 1) + b$ packets and no packet spends more than $(b + r) \cdot h \cdot (d - 1) + 1$ rounds in the system.
The next fact demonstrates that, regardless of how ties are broken, the fact that $S_{pre}$ with $T_h$ is universally stable does not imply that $S_{post}$ with $T_h$ is universally stable.

**Theorem**

The scheduling policy $SIS_{post}$ with $T_h$ is unstable against adversary $A(b, 1/(2h - 4))$, regardless of how ties are broken, where $h \geq 4$. 
Theorem

The scheduling policies $\text{SIS}_{\text{post}}$, $\text{SIS}_{\text{pre}}$, $\text{LIS}_{\text{post}}$, and $\text{LIS}_{\text{pre}}$ are all node universally stable.
The notion of a routing algorithm in radio networks

Cross-layer approach

Abstracting from transmission policies to explore universal stability of scheduling policies