A Calculus for Power-Aware Multicast Communications in Ad Hoc Networks

Sabina Rossi

joint work with
Lucia Gallina

Università Ca' Foscari - Venezia

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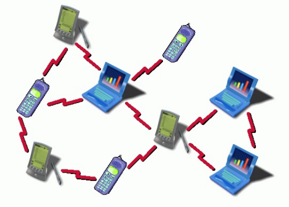
Mobile Ad-Hoc Networks



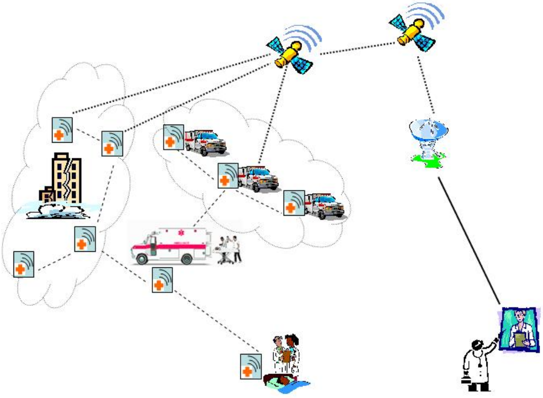
What is a Mobile Ad-Hoc Network?

A Mobile Ad Hoc Network (MANET) is a collection of wireless mobile hosts which cooperate to establish communications without using any preset infrastructure of centralized administration.

The Ad-Hoc Network Technology

- Each device in a MANET is free to move independently in any direction, and will therefore change its links to other devices frequently.
- Each node must forward traffic unrelated to its own usage, and then be a router.
- The devices communicate with each other via radio transceivers through the protocol IEEE 802.11 (WiFi).

A civilian disaster recovery scenario



The Problem of Energy Consumption

Energy efficiency is an important design criteria, since mobile nodes are often powered by batteries with limited capacity.

Energy consumption is a critical issue for the network lifetime

Power failure of a mobile node not only affects the node itself but also its ability to forward packets on behalf of others and thus the overall network lifetime.

Possible Solutions to the Problem of Energy Consumption

Energy-aware routing protocols

- using unicast and multicast communications to reduce the number of control packets
- controlling the transmission radius of nodes

Topology control

- minimizing interference

Ad hoc On-Demand Distance Vector

AODV

The main packets of this protocol are three:

- RREQ (Route Request) - transmitted via a broadcast communication
- RREP (Route Reply) - transmitted to the requester through a unicast communication
- RERR (Route Error) - a connection failure warning transmitted through a multicast communication to those devices that need to refresh their route table

Topology Control

The main goal of topology control is to reduce node power consumption in order to extend the lifetime of the network.

A trade-off between power saving and network connectivity

- Choosing a low transmission power for a node will reduce its power consumption, but it will also possibly reduce its connectivity with the other nodes in the network.
- One of the main approaches to reducing energy consumption consists in minimizing interference between the network nodes.

Related Work

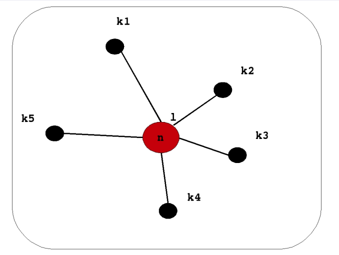
Two different approaches

- Connectivity by groups
- Connectivity by transmission area

Existing Algebraic Models

Connectivity by groups

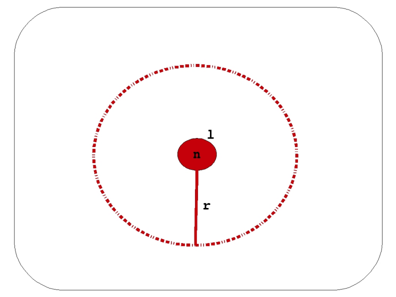
- ω-calcolus [Ramakrishnan and Smolka]
- CBS$^{\#}$ (Calculus of Broadcasting Systems) [Nanz and Hankin]
- CMAN (Calculus for Mobile Ad-hoc Networks) [Godskesen]



Existing Algebraic Models

Connectivity by transmission area

- CMN (Calculus of Mobile ad-hoc Networks) [Merro]



The E-BUM calculus

A calculus for the analysis of

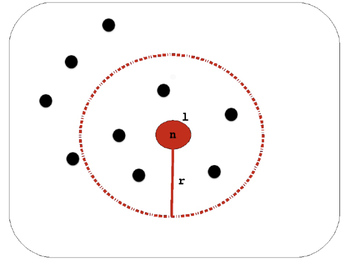
Energy-aware Broadcast, Unicast and Multicast communications

of mobile ad hoc networks.

The E-BUM calculus

Broadcast communications

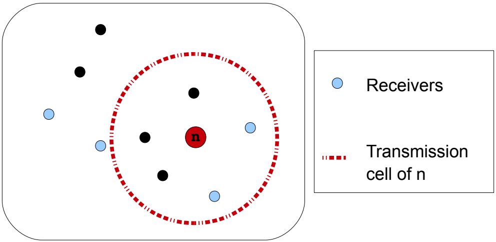
- The connectivity of a node is represented by a location and a transmission radius
- Broadcast communications are limited to the transmission cell of the sender



The E-BUM calculus

Unicast and Multicast communications

- Unicast and multicast communications are modelled by specifying, for each output action, the addresses of the intended recipients of the message.



The E-BUM calculus

Movements

- Nodes are allowed to dynamically change their physical location

Connections and Disconnections/Power Control

- Arbitrary and unexpected connections and disconnections of nodes as well as the possibility for a node to dynamically adjust its transmission power are modelled by enabling nodes to modify the corresponding transmission radius.

Connectivity Properties

We show how to use this calculus to prove some useful connectivity properties of MANETs which can be exploited to control power/energy consumption and reduce interference.

Example

We can determine the minimum transmission radius ensuring the connectivity of a node with all the intended recipients of its transmissions, thus reducing power consumption.

The E-BUM model

Features

- Broadcast, Unicast and Multicast communications
- Movements
- Arbitrary connections and disconnections of nodes
- Power control

Syntax

Nodes

$$n[P]_{l,r}$$

P: process executed in n

l: physical location

r: transmission radius

n: $\langle r_n, \delta_n \rangle$

r_n: maximum transmission radius

δ_n: maximum distance that a node can cover in a computational step

$r_n = 0$	$\Rightarrow$	the node is corrupted
$r = 0$	$\Rightarrow$	the node is disconnected
$\delta_n = 0$	$\Rightarrow$	the node is stationary

Syntax

Processes are sequential and live within the nodes.

Processes

$P ::= \mathbf{0}$	Inactive process
$\mid c(x).P$	Input
$\mid \bar{c}_{S,r}\langle v \rangle.P$	Output
$\mid [w_1 = w_2]P, Q$	Matching
$\mid A\langle v \rangle$	Recursion

Syntax

Networks are collections of nodes, running in parallel and using channels to communicate messages.

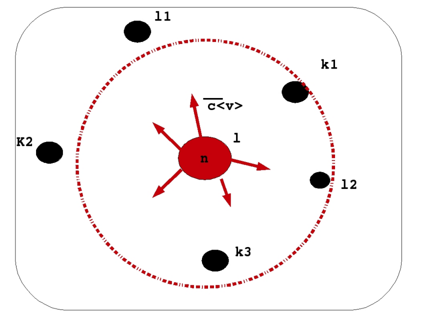
Networks

$M,N ::= \mathbf{0}$	Empty network
$\mid M_1 \mid M_2$	Parallel composition
$\mid n[P]_{l,r}$	Node (or device)

Output action

Broadcast with fixed radius

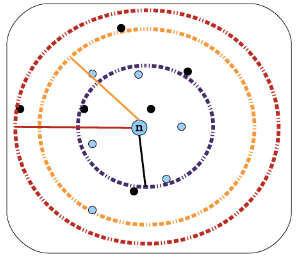
$$M \xrightarrow{\bar{c}\langle v\rangle} M'$$



Output action

Multicast with variable radius

$$M \xrightarrow{\bar{c}\,\mathbf{S},\mathbf{r}\langle v\rangle} M'$$



Reduction Semantics

Broadcasting

The recipients set S indicates the nodes which are really interested in receiving the message. The cardinality of S indicates the kind of communication: unicast, multicast, broadcast.

Transmission

$$\frac{d(l, l_i) \leq r,\ \ r \neq 0,\ \ r_i \neq 0}{n[\bar{c}_{S,r}\langle v\rangle.P]_{l,r} \mid \prod_{i\in I} n_i[c(x_i).P_i]_{l_i,r_i} \rightarrow n[P]_{l,r} \mid \prod_{i\in I} n_i[P_i\{v/x_i\}]_{l_i,r_i}}$$

Reduction Semantics

Arbitrary and Unpredictable Movements

Nodes are free to move independently in any direction, and will therefore change their links to other devices frequently.
A node n is a mobile node when $\delta_n > 0$

Changing location

$$\frac{}{n[P]_{l,r} \rightarrow n[P]_{k,r}} \quad 0 \leq d(l,k) \leq \delta_n \quad r \neq 0$$

Reduction Semantics

Power Control/Arbitrary Connections and Disconnections

The possibility for a node n to control its power consumption is modeled by enabling it to modify its transmission radius r into r' provided that $0 \leq r' \leq r_n$. This allows us also to model arbitrary connections and disconnections of nodes.

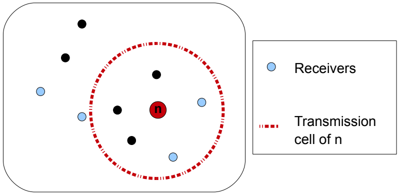
Variable Radius

$$\frac{}{n[P]_{l,r} \rightarrow n[P]_{l,r'}} \quad 0 \leq r' \leq r_n$$

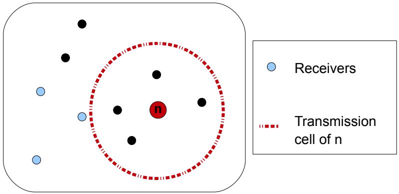
Observation Semantics

A transmission is observable only if at least one of its intended receivers is actually able to receive the message.

Observable action



Non-observable action



Observation Semantics

Let $M \equiv n[\bar{c}_{S,r}\langle v\rangle.P]_{l,r}|M'$

Barb

$$\mathbf{M \downarrow_c}$$

if $\exists k \in S$ and $d(l,k) \leqslant r$.

If $M \equiv (n[\bar{c}_{S,r}\langle v\rangle.P]_{l,r}|M')$ and $M \downarrow_c$ then at least one of the recipients in S is actually able to receive the message.

Observation Semantics

Equivalence relative to intended receivers

Two networks are equivalent if they exhibit the same behaviour relative to the sets of their intended recipients.

Reduction barbed congruence

Reduction barbed congruence, written $\cong$, is the largest symmetric relation over networks, which is

- reduction closed
- barb preserving
- contextual

Bisimulation-based Proof Technique

It provides an efficient method to check whether two networks are equivalent.

Bisimilarity $\approx$

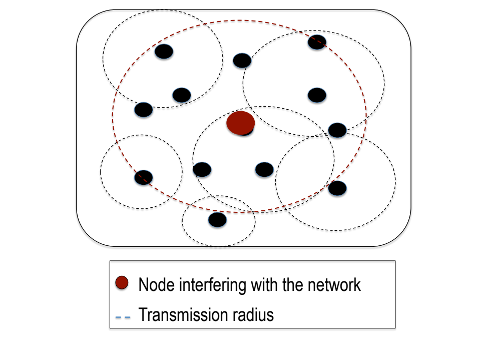
$$M \cong N \text{ iff } M \approx N$$

Energy-aware Properties

- Absence of interference
- Minimum radius of maximum observability
- Simulation of stationary nodes
- Complete range repeaters

Interference

A node with a too large transmission radius may disturb the other transmissions within the network



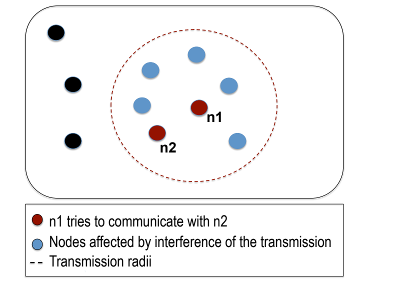
Interference

Two notions of Interference

- *Sender-centered Interference*: measures the number of nodes potentially disturbed by the sender of a message
- *Receiver-centered interference*: measures the number of nodes potentially disturbing a given receiver

Sender-centered Interference

How many nodes are disturbed by a given communication over the network?



Sender-centered Interference

Let $\bar{c}_{S,r}\langle v \rangle$ be an output action and $K = \{k : \ d(l,k) \leq r\}$.

Level of Sender-centered Interference

The *level of Sender-centered Interference* relative to this output is:

$$I_{send}(\bar{c}_{S,r}\langle v \rangle) = |K - S|.$$

If $I_{send}(\bar{c}_{S,r}\langle v \rangle) = 0$ then $\bar{c}_{S,r}\langle v \rangle$ does not provoke any interference.

Absence of Sender-centered Interference

Let $brd(P)$ denote the process P but broadcasting all its messages to the whole network, e.g., $brd(\bar{c}_{S,r}\langle v\rangle.P') = \bar{c}_{\infty,r}\langle v\rangle.brd(P')$.

Definition

We say that a node $n[P]_{l,r}$ is free of *Sender-centered interference* if

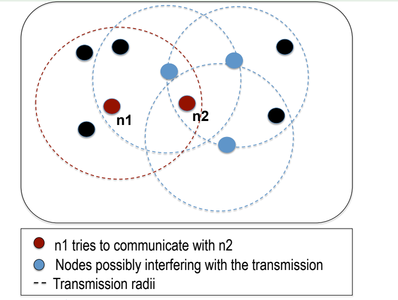
$$n[P]_{l,r} \cong n[brd(P)]_{l,r}$$

Theorem [Soundness]

If $n[P]_{l,r}$ is free of *Sender-centered Interference* then for all output actions $\bar{c}_{S,r}\langle v\rangle$ performed by $n[P]_{l,r}$ holds $I_{send}(\bar{c}_{S,r}\langle v\rangle) = \emptyset$.

Receiver-centered Interference

How many nodes disturb a given communication over the network?



Receiver-centered Interference

Let M be a network consisting of k devices:

$$M = n_1[P_1]_{l_1, r_{n_1}} \mid \dots \mid n_k[P_k]_{l_k, r_{n_k}}$$

Level of Receiver-centered Interference

The *level of Receiver-centered Interference* with respect to a given location l is:

$$I_{rec}(l, M) = |\{j \in \{1, \dots, k\}.\ d(l, l_j) \leq r_{n_j} \ \wedge \ l \notin \mathtt{r}(P_j)\}|$$

where $\mathtt{r}(P_j)$ denotes the set of intended recipients of P_j.

Absence of Receiver-centered Interference

Let $brd(M, l)$ denote the network M but adding l as an intended receiver of all its messages.

Definition

The location l is free of *Receiver-centered Interference* w.r.t. M if

$$M \cong brd(M, l).$$

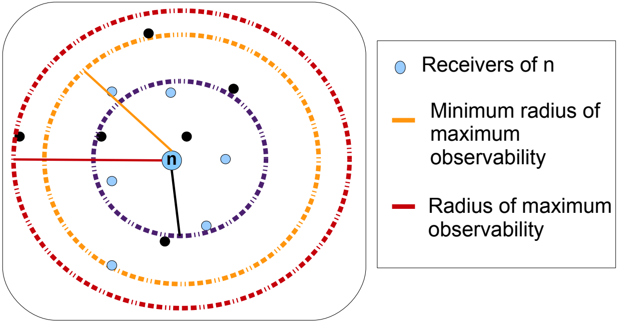
Theorem [Soundness]

If l is free of *Receiver-centered Interference* with respect to M, then

$$I_{rec}(l, M) = 0.$$

Radius of Maximum Observability

Different radii



Radius of maximum observability

Let $n[P]_{l,r_n}$ be a stationary node with $\delta_n = 0$ located at l.

Property

Suppose that $d(l,k) \leq r_n$ for all $k \in \mathtt{r}(P)$. Then:

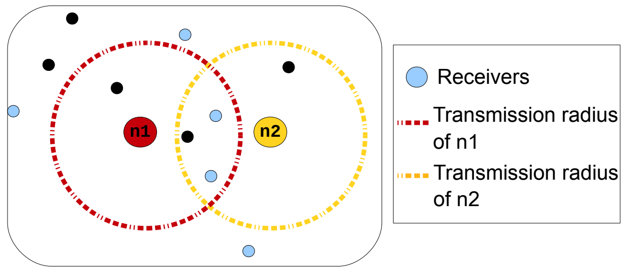
$$n[P]_{l,r_n} \cong m[P]_{l,r_m}$$

for every node m such that $r_m \geq r_n$ and $\delta_m = 0$.

In this case r_n is a radius of maximum observability for the node n.
The minimum radius of maximum observability for n corresponds to the distance between n and the most distant recipient.

Simulation of stationary nodes

Simulation of stationary nodes in different locations



Simulation of stationary nodes

Let $n[P]_{l_n,r_n}$ and $m[P]_{l_m,r_m}$ be stationary nodes with $\delta_n = \delta_m = 0$.

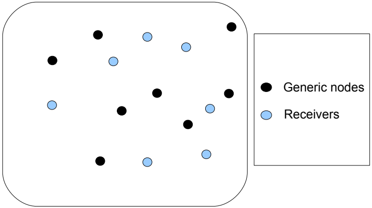
Property

Let $R_n = \{k \mid d(l_n, k) \leq r_n \wedge k \in \mathtt{r}(P)\}$ and $R_m = \{k \mid d(l_m, k) \leq r_m \wedge k \in \mathtt{r}(P)\}$. Then

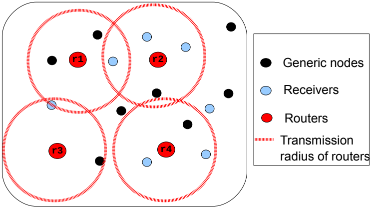
- $R_m \subseteq R_n$ iff $n[P]_{l_n,r_n}$ simulates $m[P]_{l_m,r_m}$
- $R_m = R_n$ iff $n[P]_{l_n,r_n} \cong m[P]_{l_m,r_m}$

Example of optimising routers allocation

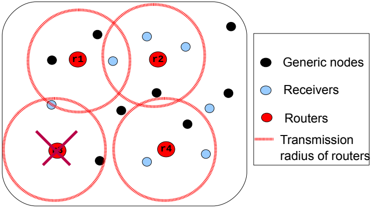
(a) initial network topology



(b) First routers allocation



(c) Optimal routers allocation

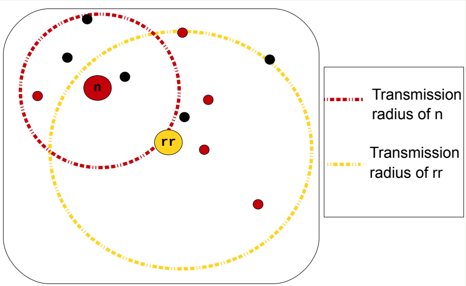


Range Repeaters

Informally

Range repeaters are devices which regenerate a network signal in order to extend the range of the existing network infrastructure

Example



Range Repeaters

Let c be a channel, l a location, r a transmission radius and S a set of locations.

Definition

A repeater for S located at l with transmission radius r is a stationary device, denoted

$$rr[c \hookrightarrow_{S,r} c]_{l,r}$$

with

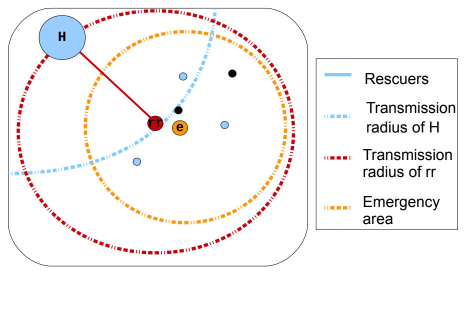
$$c \hookrightarrow_{S,r} c \stackrel{\text{def}}{=} c(x).\bar{c}_{S,r}\langle x\rangle.c \hookrightarrow_{S,r} c.$$

Complete Range Repeaters

Definition

A range repeater $rc[c \hookrightarrow_{S,r} c]_{l,r}$ is said complete w.r.t. a set of receivers S if $S \subseteq K$ where $K = \{k : \ d(l,k) \leq r\}$.

Example



Conclusion

One of the most critical challenges in managing mobile ad hoc networks is to find a good trade off between network connectivity and power saving.

How can we use our model:

- to compare different protocols in terms of energy consumption
- to develop new cost effective communication strategies

How can we extend our model:

- adding a measure for the power consumption
- adding probabilities to represent node movements