Broadcast with Network Coding

Selected Results

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Motivation

- Part of Hipercom Team Efforts: routing protocols for wireless multi-hop networks
  - ex: OLSR
- Also multicast and broadcast:
  - Send to one source to several/all nodes in the network

Multicast and Broadcast

Example: for DGA (French MoD), simul. of 3 multicast protocols

- SMOLSR: a subset of nodes repeat source packets (= OLSR)
- MOLSR: a shortest-path tree (within OLSR)
- MOST: an overlay tree is built (minimum spanning tree)
- A. Meraihi-Naimi, C. A., P. Minet and G. Rodolakis, *Simulation-Based Comparison of Three Wireless Multicast Routing Protocols: MOST, MOLSR and SMOLR*, ADHOC-NOW'2010

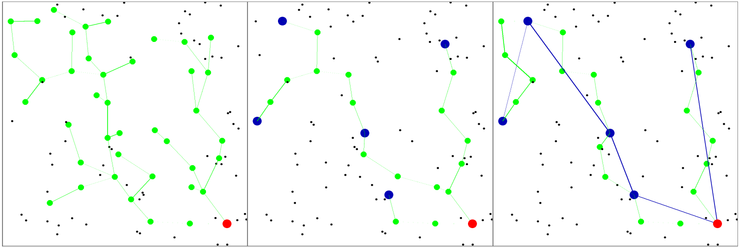
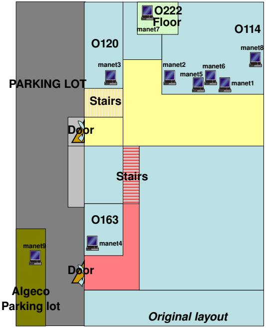


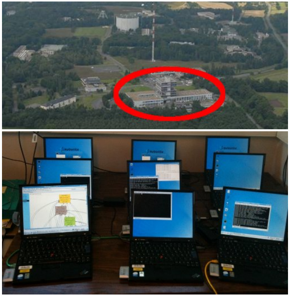
Figure: SMOLSR (41 t.), MOLSR (18 t.), MOST (22 t.)

Multicast and Broadcast - Experiments

Experiments

- A. Meraihi-Naimi, C.A., P. Minet, T. Plesse, *"Experiments with the MOST multicast protocol in a Wireless Multi-hop Network"*, IWCMC'2011
- Testbed deployed at DGA/MI (French MoD).

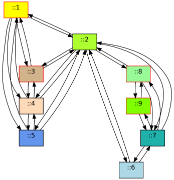


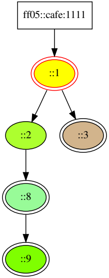


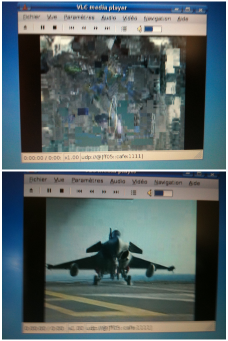
Multicast and Broadcast - Experiments

Experiments with MOST

- OLSRv2 topology: 4-hops.
- MOST tree built with node '::1', '::3', '::8', and '::9'



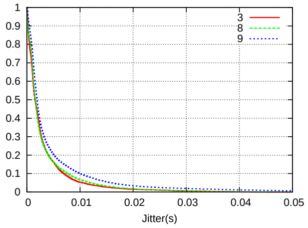




Multicast and Broadcast - Experiment Lessons

Emulation of audio-conference traffic

- G.729 emulation: payload 10 bytes, sampling 10 ms
- Low loss rate $< 1\%$
- Min. per hop forwarding < 1 ms
- Complementary cumulative distribution function
- Maximum jitter 50 ms / 90 ms
- For $> 90\%$ of packets, jitter < 10 ms: fully satisfactory



What about network coding?

Broadcast with Network Coding

Overview of Results for Network Coding

- Before 2008:
  - Theoretical results for specific "MANET model": energy-efficiency
- 2008-2012:
  - Generalized theoretical results in the specific models
  - Designed adaptive broadcast protocol (DRAGONCAST), simulations
- 2012-:
  - Practical network coding protocols
    Ex: for WSN and for military networks (ex context: GETRF)

Network Coding: Selected Results

Results on broadcast with network coding in "MANET model":

- What is the expected performance of network coding?
- How to obtain good performance with network coding?
- How does it compares with routing?

References

- C. A., S.-Y. Cho and P. Jacquet, *"Near Optimal Broadcast with Network Coding in Large Sensor Networks"*, WITS'07.
- C. A. and S.-Y. Cho, *"Wireless Broadcast with Network Coding: A Connected Dominating Sets Approach"*, Inria, RR-6547, June 2008
- P. Jacquet, C. A. and S.-Y. Cho, *"Performance of Network Coding in Lossy Wireless Networks"* Inria-00382154, October 2008.
- C. A. and S.-Y. Cho *"Wireless Broadcast with Network Coding: Energy Efficiency, Optimality and Coding Gain in Lossless Wireless Networks"*, RR-7011, July 2009.

Theoretical Result – Problem Statement

Considered Problem

- Broadcast with Network Coding
  - Send information
    - from one source (single-session)
    - to all nodes in network
  - Packet network

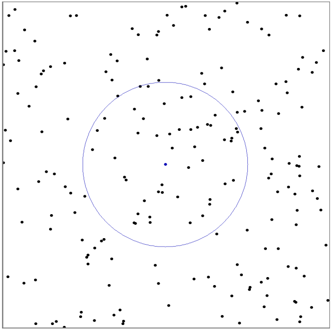
Goal

- Efficiency
- Minimize the total number of transmissions for broadcasting one packet from the source

Theoretical Result – Assumptions

Assumptions (“MANET model”)

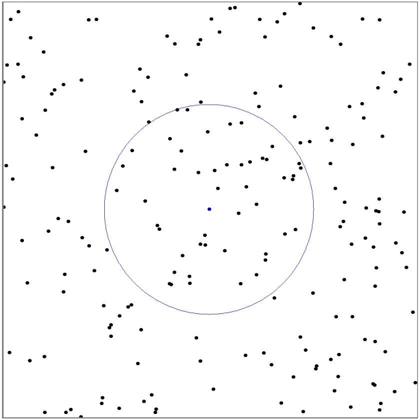
- Ideal model (no fading, no losses)
- Ignore interferences, scheduling, spatial reuse, . . .
  - Approx.: CSMA/CA, TDMA, or far from capacity limit
- Goal: Minimize number of transmissions
- Very different from capacity $\rightarrow$ energy-efficiency
- Heuristic for min. channel use (e.g. ETX metric)



Broadcast without Network Coding

Example of Broadcast without Network Coding

- Some subset of nodes retransmits messages
- Minimizing the number of retransmitting nodes
- Connected Dominating Set
- in OLSR:
  Multi-Point Relays
  → MPR Flooding
  actually dynamic
  self-elimination



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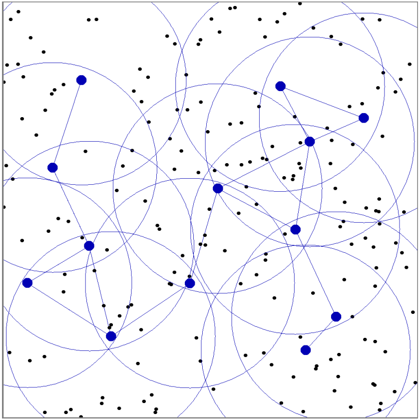


Broadcast with Network Coding

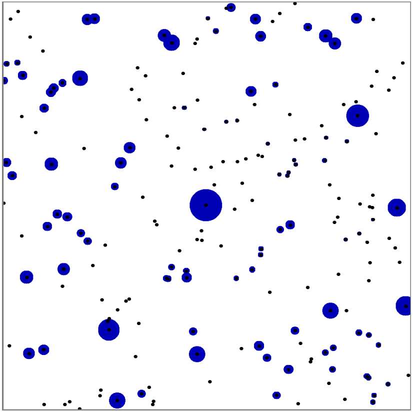
With Network Coding

- With assumptions, applying network coding theory [Lun et al'08]:
- Optimal performance may be achieved by RLC; for instance:
  - the source sends K packets periodically
  - every node retransmits combinations of packets periodically with a given packet retransmission rate
- Performance (energy-efficiency) is entirely defined by packet retransmission rate of each node
- *Maximum broadcast rate* of the source r:
  is capacity of the min-cut (on hypergraph)
  - the source can select an arbitrary rate $r' < r$
  - the nodes can decode with probability $\rightarrow 1$ when $K \rightarrow \infty$

Broadcast with Network Coding

With Network Coding

- Optimal packet rates may be computed:
- linear program (from [Lun et al.'06])
  - Source rate = 1
  - Total rate = 9.0625



Results about Network Coding

- What is the expected performance of network coding?
  - Property of optimality at the microscopic scale
  - Th: Network coding operates optimally in part of the network (asymptotically)
  - When area of the network grows, the part represents the majority
- How to obtain good performance with network coding?
  - Selection of packet rate proposed for the previous results
- How does it compares with routing?
  - (Asymptotic) energy-efficiency gain

Main Theme: Optimality at a microscopic scale

Optimality at a microscopic scale

- One transmission reaches several neighbor nodes
- Efficiency (at the trans. level): useful for several nodes
- Innovative $\triangleq$ useful
- Transmission-level optimality $\triangleq$ the transmission is useful for every receiver

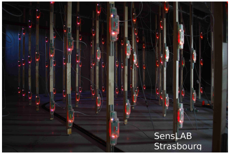
Link with the goal: bound

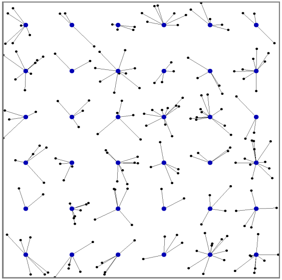
- N nodes, M maximum number of neighbors
- $\geq \frac{N}{M}$ transmissions necessary for broadcast (bound)

Introduction of Discrete Geometry

Lattice

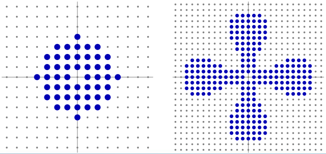
- Deliberate node placement
- or mapping to a lattice:
  - "Virtual lattice": mapping in sufficiently dense network
  - adjust radio range
  - CDS of transmitters





Neighborhood

- Identical by translation ; Sym.

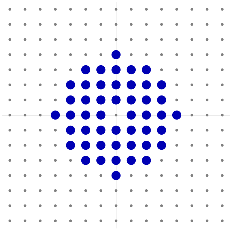


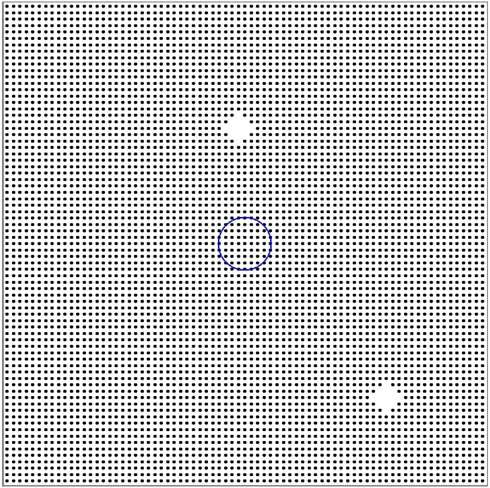
Example of network

Example

- Lattice network
- (Max) Number of neighbors: $M = 48$

Neighborhood

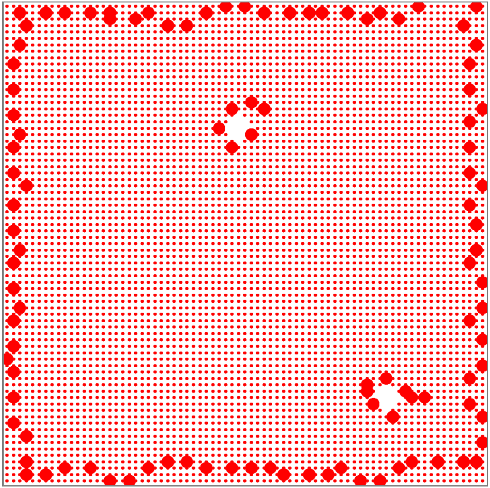




Selection of Packet Rate

Packet rate selection

- Identify “border” nodes
- CDS construction:
  - Cover border nodes
- Network coding:
  - Every node retransmits: 1
  - Some more (CDSs): M



Main result

Theorem

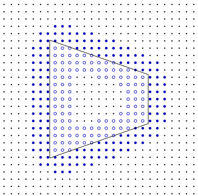
- For such packet rate selection,
  for a source s (and any destination t),
  the capacity of the min-cut on the [hyper]-graph is M

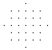
Consequence

- Max. broadcast rate of the source is exactly M

Proof

- through discrete geometry
- any (symmetric) neighborhood

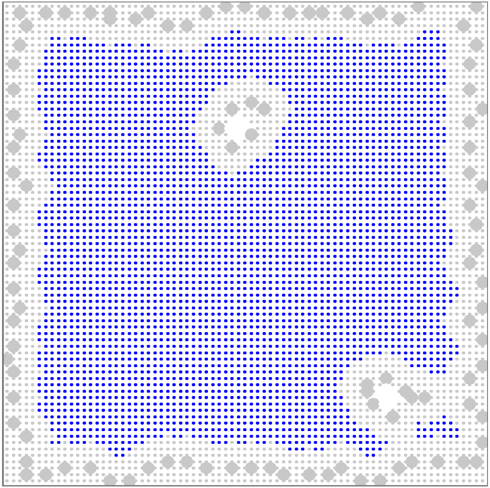




Consequence (efficient reception)

Consequence (receivers)

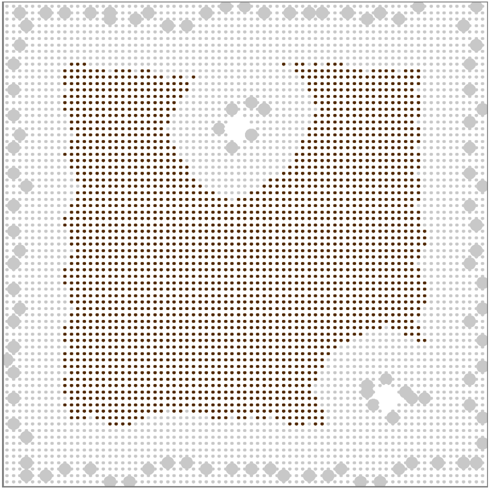
- Source rate $\rightarrow M$
- Highlighted nodes have M neighbors with rate 1
- Proportion of received innovative packets $\rightarrow 1$



Consequence (efficient transmission)

Consequence (transmitters)

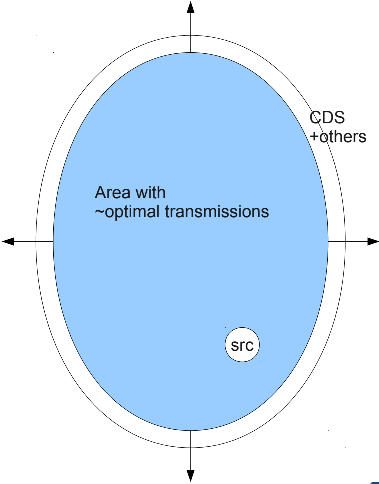
- Source rate $\rightarrow M$
- Highlighted nodes have neighbors, with only neighbors with rate 1
- Proportion of transmitted packets that are innovative for all neighbors $\rightarrow 1$
- Optimality at the microscopic scale



Consequence (area $\to \infty$)

Energy-efficiency and asymptotic optimality

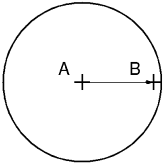
- Lattice subset with constant neighborhood
- Area $\to \infty$
- Area of "border" is $\Theta(\sqrt{Area})$
- Avg. prop. of innovative transmissions $\to 1$
- Energy-efficiency converge towards the bound = "the network is asymptotically operating optimally"
- Similar results also for spatial Poisson process (with proper density increase)



Comparison with Routing

- Transmissions with routing cannot be optimal at the transmission-level

[Widmer et al. 2005]



Comparison with Routing

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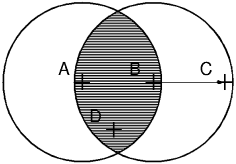
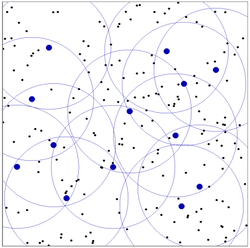
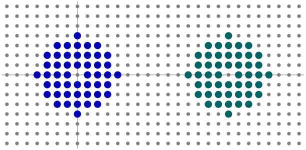


Comparison with Routing

- Assuming:
  - Unit-disk neighborhood R with $R \to \infty$
  - Lattice in a square length L with $L \to \infty$
- Energy-efficiency coding gain in dim 2: between 1.642 and 1.684
- Energy-efficiency coding gain in dim 3: between 1.432 and 2.035
- (E-E. gain in dim n: $\Omega(n)$)



Lessons for protocols



- Hints for packet rate selection
- For broadcasting with network coding, considering between the source s and a destination t
  - Not only nodes on the shortest paths have an impact
- Further results (using more discrete geometry): assuming s and t can communicate instantly and without cost with their neighborhood,
  - the capacity of min-cut $\geq 2M - 3$ [in dim 2]
  - higher than M ; bottleneck is at the source/destination
  - some tolerance to losses, sufficient to recover losses locally

Examples of Some Other Results

- Study of real network coding protocols (by simulation)
  - S.-Y. Cho, C. A., *"Wireless Broadcast with Network Coding in Mobile Ad-Hoc Networks: DRAGONCAST"*, Med-Hoc-Net 2008, June 2008
- Study of Fairness with network coding (multiple session)
  - G. Karbaschi, A. Carneiro-Viana, S. Martin, and K. Al Agha. *On using network coding in multi-hop wireless networks.* IEEE PIMRC. September 2009.
- Model with Losses
  - P. Jacquet, C. A., S.-Y. Cho, *"Performance of Network Coding in Lossy Wireless Networks"* Inria-00382154, October 2008.

Broadcast Protocol with Network Coding: DRAGONCAST

Our approach

- An heuristic for finding the rates of each node
- Rate adjusted with a feedback control:
  D.R.A.G.O.N. (Dynamic Rate Adaptation from Gap with Other Nodes)
- Simple, dynamic, and generic
  - Simple: uses only information from the state of neighbors
  - Dynamic: allows for topology change, transient losses, . . .
  - Generic: actually no assumptions (interference, mobility, loss probability)

Our Approach

Normal behavior of network coding

- Assuming coded packets are propagated properly:
- The ranks in every node should increase homogeneously

Idea

- Perform a control:
  - Detection: check if the ranks of two nodes are not sufficiently close to each other
  - If so: remedy the situation
- Acting locally: between neighbors

Mechanism for Control

Principle of the Control

- When a node has a neighbor with a lower rank
- $\rightarrow$ It increases its rate
- $\rightarrow$ This will tend to close the gap
- Underlying property:
  - If a node u with higher rank transmits packets to a node v with lower rank, its packets will be innovative for v
  - Note: in the opposite direction, it may or may not be the case
  - This is an argument for energy-efficiency
- Heuristic: the increase of rate is proportional to the size of the gap
- Tends to equalize the ranks in each node globally

Details of DRAGON

Detail of the algorithm

- D.R.A.G.O.N - Dynamic Rate Adaptation from Gap with Other Nodes
- The node u memorizes the rank of the nodes of its neighbors: D_v for $v \in H_u$ (where H_u = neighbors of u)
- The node considers the largest gap between its rank D_u and the ranks of its neighbors:

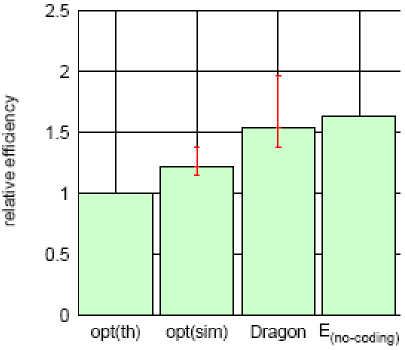
$$g'_u = \max_{u \in H_u} \frac{1}{|H_u|}(D_v - D_u)$$

- If $g_u > 0$: rate of the node is set to $C_v = \alpha g_u$
- Delay is approximated as $\frac{1}{C_v}$

Broadcast Protocol with Network Coding: DRAGONCAST

Example: performance of DRAGON, cost

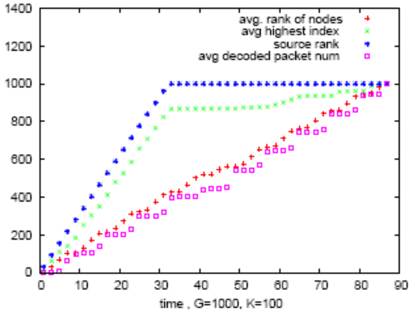
- Simulations with NS2
- N=200 ; M=20 ; #sim=10
- Relatif cost, ref. optimal
- Theoretic Optimal opt(th)
- Optimal simulations opt(sim)
- DRAGONCAST
- Approx. bound no coding



Performance of DRAGONCAST

Example: performance de SEW, decoding

- Simulations with NS2
- Amount of received information
- Number of decoded packets

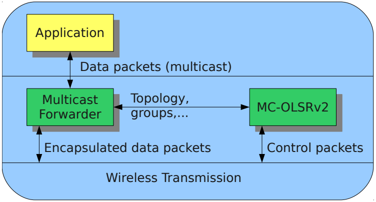


THANK YOU

Multicast and Broadcast - Protocol Design

Protocol Design and Implementation for MOST with OLSRv2

- Signaling - with OLSRv2:
  - Diffusion of the group membership
    - Simple with OLSRv2 (actually Packet-BB) message formats
    - Cost: a fraction of the OLSR control overhead
  - Resilience to topology changes
    - History of overlay trees (soft-state: a tree is valid for a duration) $\rightarrow$ mesh
    - Requirement: loop prevention mechanism
- Implementation: OLSRv2 $\rightarrow$ MC-OLSRv2 + MOST



Multicast and Broadcast - Experiment Lessons

Pinpoint an important practical aspect: MAC layer behavior

- "Elephant Dream", 128 kbps
- Scenario with transmissions:
  - $1 \rightarrow 3$ and $1 \rightarrow 6 \rightarrow 7 \rightarrow 9$
- MAC layer statistics:

*	1 Mbps	18 Mbps	24 Mbps	36 Mbps	48 Mbps	54 Mbps	Retry	Signal (RSSI)
$1 \rightarrow 3$	0.2%	0.0%	0.5%	13.8%	35.8%	48.8%	4.6%	-37.9 (std dev=3.7)
$1 \rightarrow 6$	0.8%	2.2%	18.6%	44.6%	12.1%	21.1%	10.6%	-65.3 (std dev=2.5)
$6 \rightarrow 7$	4.6%	-	26.2%	69.2%	-	-	26.2%	-64.6 (std dev=1.6)
$7 \rightarrow 9$	0.1%	3.6%	13.5%	76.1%	4.8%	0.0%	7.0%	-62.1 (std dev=1.3)

- Actual rate range from 1 Mbps to 54 Mbps
- Rate adaptation algorithm Minstrel operates with packet loss 4% – 26%, even though end-to-end MOST PDR is 99.6%
- Minstrel successfully avoids 54 Mbps rate on link $6 \rightarrow 7$

Multicast and Broadcast - Experiment Lessons

MOST Overlay features

- Overlay: decoupling between unicast and multicast routing
- Benefits from improvements of the unicast routing
- Uses unicast transmissions (no need for MOST everywhere)

Neighborcast – vs – Unicast

- Neighborcast: one transmission reaches several neighbors
- Advantage: *wireless multicast advantage*
  - less transmissions required
- Drawbacks: *coping with losses*. In most wireless technologies:
  - several modulations (physical layers) are available
  - neighborcast is performed with a safe modulation (lower rate)
  - unicast has a rate control algorithm: modulation is adjusted depending on losses

Examples of Some Other Results

- Study of jitter with broadcasting

  J.A. Cordero, P. Jacquet, E. Baccelli, *"Impact of Jitter-based Techniques on Flooding over Wireless Ad hoc Networks: Model and Analysis"*, INFOCOM 2012

- Broadcast in VANETs

  A. Laouiti, P. Muhlethaler and Y. Toor, *"Broadcast Techniques for Vehicular Ad Hoc Networks"*, Wireless technologies in intelligent transportation systems Nova Science (Ed.) (2011) pp205-222

- Multicast with quality of service

  G. Rodolakis, C. A., A. Laouiti, and S. Boudjit, *"Quality-of-Service Multicast Overlay Spanning Tree Algorithms for Wireless Ad Hoc Networks"*, AINTEC, Nov. 2007

- . . .

- $A \oplus B$ is defined as the set of all vector sums generated by all pairs of points in A and B, respectively:

$$A \oplus B \triangleq \{a + b \mid a \in A, b \in B\} \tag{1}$$

- Inequality: For two non-empty subsets A, B of the integer lattice $\mathbb{Z}^n$,

$$|A \oplus B| \geq |A| + |B| - 1 \tag{2}$$

- Ruzsa proved:
  For two finite subsets A, B of the integer lattice $\mathbb{Z}^n$, with $|B| \leq |A|$ and $dim(A \oplus B) = n$, then

$$|A \oplus B| \geq |A| + n|B| - \frac{n(n+1)}{2} \tag{3}$$

Link Quality Statistics