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Wireless Sensor Networks: Recent Trends and Research Issues

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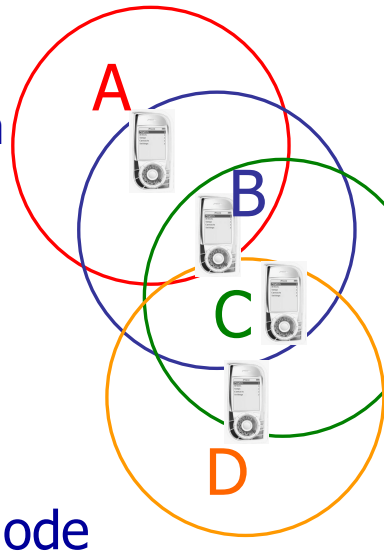
Outline

- Wireless Sensor and Actuator Networks (WSANs)
  - The ad hoc paradigm, uses, and applications
- Technical issues and research challenges in WSANs
- The "Future Internet" and WSAN's role
- Work in progress on WSANs within the SIGNET group
  - Cross-layer MAC-routing protocols
  - Network reprogramming
  - Large testbed for city-wide applications

Wireless Ad Hoc Networks

- *Ad Hoc* = Latin for *as needed*: non-fixed networks, no infrastructure, no centralized management, no predefined contracts
- Ad hoc network
  - Collection of wireless terminals that communicate through a shared common access medium using distributed protocols
  - **Pros**: Flexibility, seamless networking anywhere, including business meetings, emergencies/disasters, rescue ops., community networks, …
  - **Cons**: hidden/exposed terminal, MAC and routing design, inefficiencies, protocol design needs, market?



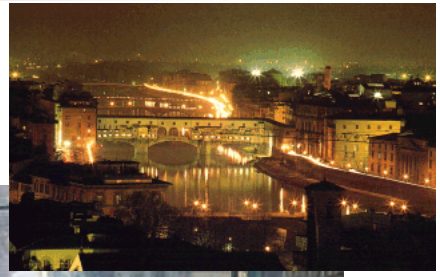
- Example: the IEEE 802.11 standard includes an ad hoc mode
  - Contention- or handshake-based (prone to errors, low spatial reuse)
- Research in this field is quite mature from different points of view
  - MAC & routing protocols for ad hoc networks (random vs synchronized access, proactive vs reactive routing, …)
  - cross-layer design of MAC/routing, resource allocation…

Wireless Sensor (and Actuator) Networks

- Wireless ad hoc networks of small nodes mostly used for distributed monitoring, extended sensing, surveillance, ambient intelligence, …
- Nodes are usually more constrained than in a standard ad hoc network
  - Size, computing power, transmit rate, memory, energy supply
- Communication protocols must take this into account and be very efficient in order to save resources, e.g.:
  - Reduction of idle channel sensing times
  - Reduction of contentions and relay selection procedure
  - Intelligent duty cycling (wake up as needed, adapt duty cycle to traffic)
- Sensor boards: TmoteSKY, EYES, MICA, XBOW,…

Examples of applications for WSNs - 1

- Traffic control and road conditions along a path
  - Weather information, air pollution, level of noise, light, visibility …
  - Closest taxis, public transportation info, services to tourists, …



- Personal health and utility networks
  - Localization of hidden/lost/stolen objects
  - Health and safety assistance to elders

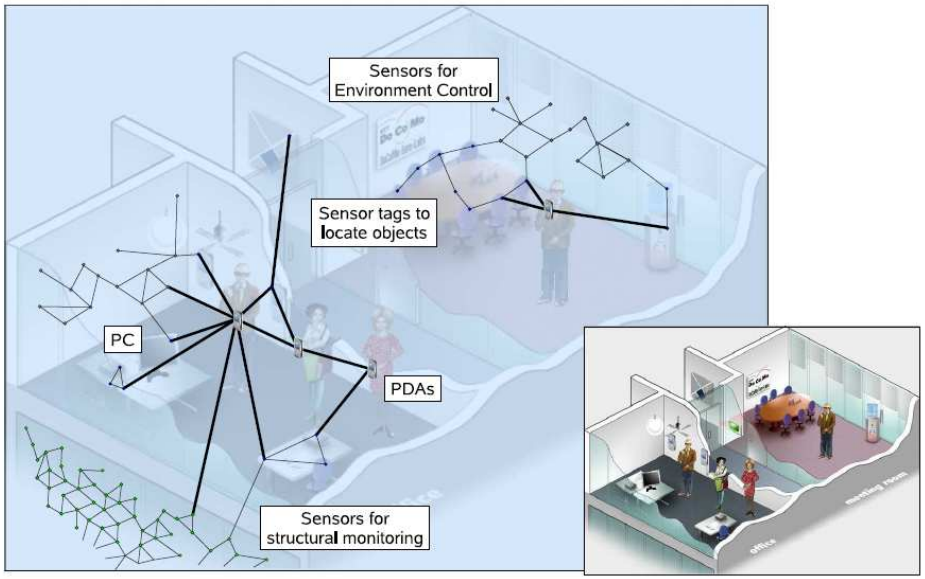
- Forest fire detection, avalanche risk assessment, wildlife

Examples of applications for WSNs - 2

- Assembly line
  - **Substitute cabled machinery** with wireless sensors
  - **Real time environment control** (pressure, gas, chemical agents)
  - **Real time production control** of machinery and process efficiency
  - **Security:** real-time detection/tracking of movements inside factory
  - **Energy savings:** consumption monitoring; redistribution of workload to optimize consumption (e.g., *minimization of peak power required by the assembly line*)
  - **Fault prediction:** continuous monitoring of the machinery conditions

Examples of applications for WSNs - 3

- Lost & Found
  - Determine the position of objects inside a building
  - Track people in a certain area (a street, a city)
- The Smart House
  - Adaptive and fine-grained monitoring of consumptions
  - Consumption control for comfort and energy savings



Examples of applications for WSNs - 4

- The mall
  - Many heterogeneous devices can be present at the same time
    - ✓ Laptops, PDAs, cell phones
    - ✓ Wireless sensors
    - ✓ Smart tags and RFIDs
  - Users querying for generic (e.g., car tools) as well as specific (e.g. latest Pavarotti live) products
  - Users propagate their interests
  - The network must self-organize and cooperate to build a continuously evolving information database (WSN as a search engine?)
  - Proactive and reactive advertisements
    - ✓ Special offers, directions, latest news
    - ✓ User-required information on the mall (e.g., for a specific shop)

Evolution of WSAN's applications and features

- Older/initial view (e.g., environmental monitoring):
  - Single system, relatively homogeneous
  - Simple (almost disposable) devices – energy as main driver
  - Special-purpose and optimized (e.g., networking protocols)

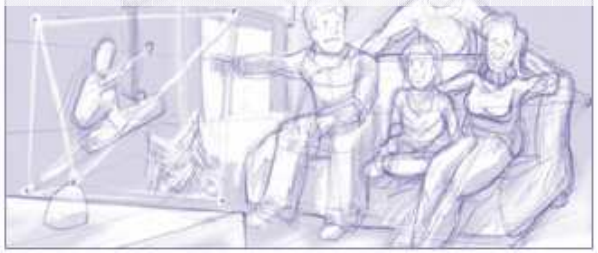
Evolution of WSAN's applications and features

- Older/initial view (e.g., environmental monitoring):
  - Single system, relatively homogeneous
  - Simple (almost disposable) devices – energy as main driver
  - Special-purpose and optimized (e.g., networking protocols)
- This is no longer the case… instead,
  - Pervasive infrastructure of heterogeneous nodes (capabilities, transmission capacity, memory, energy, sensing, …)
  - No single owner necessarily, need for standard comm paradigm
  - Provides capabilities, functionalities and service creation environment rather than vertical applications
  - User value and service creation capabilities as main driver?
  - Part of a larger system: Future Internet (Networked Society)
  - Capturing context a key component – "googling physical reality"?

An example: e-Sense

- *e-SENSE* enables capturing of Ambient Intelligence for Beyond 3G Mobile Communication Systems through Wireless Sensor Networks
- http://www.ist-esense.org/ FP6, IST-4-IP-027227

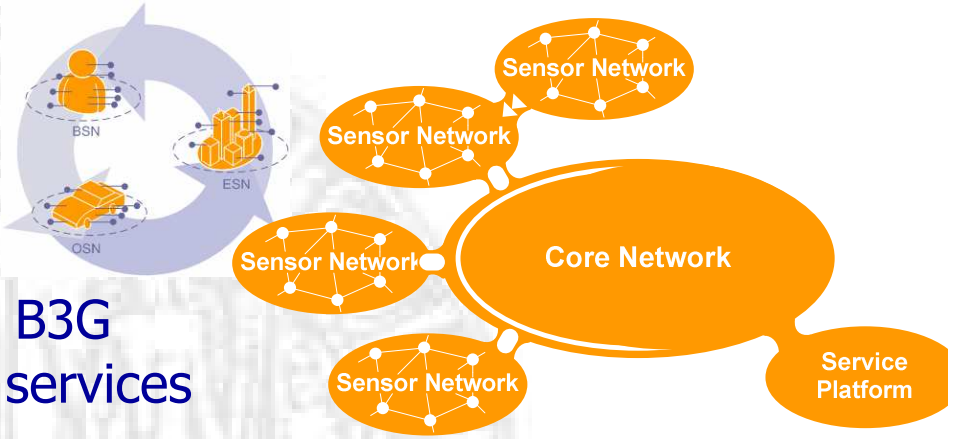
Personal application space



Community application space

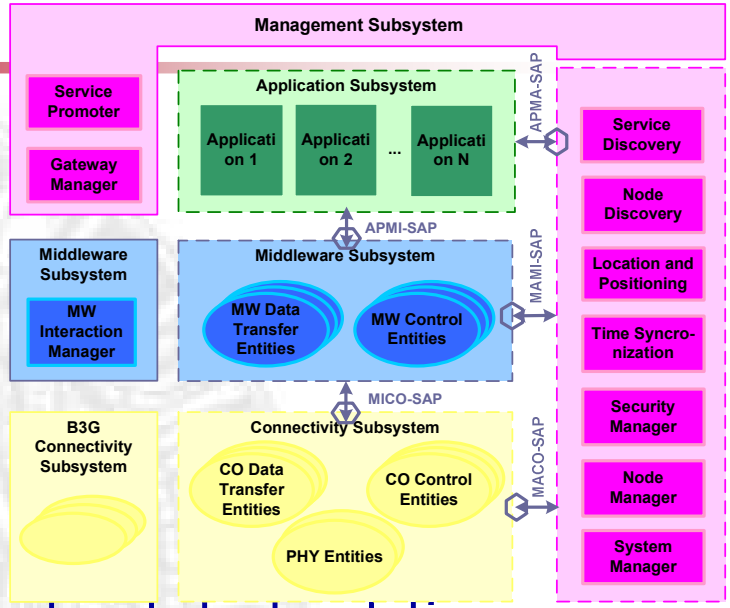
Industrial application space

Vision and key objectives of e-SENSE



- Efficient Wireless Sensor Networks
- Heterogeneity of Sensor Networks
  - Body, Object and Environment Nets
- Integration of Sensor Networks into B3G
- Ambient Intelligence to enable new services
- Key objectives:
  - **Socio-economic and psychological impact** linked with scenario building, user testing and specification of top level requirements
  - **Energy and bandwidth efficient, wireless sensor communications:** improving the energy efficiency of the air interface for wireless sensor networks, 20nJ/bit.
  - **Scalable and reconfigurable transport of data:** MAC-transport protocol stack with better efficiency and better scalability than ZigBee
  - **Distributed processing middleware:** management of resources, pre-processing of data, situation aware applications and services, programming paradigms to re-task sensors
  - **End-to-end system integration**

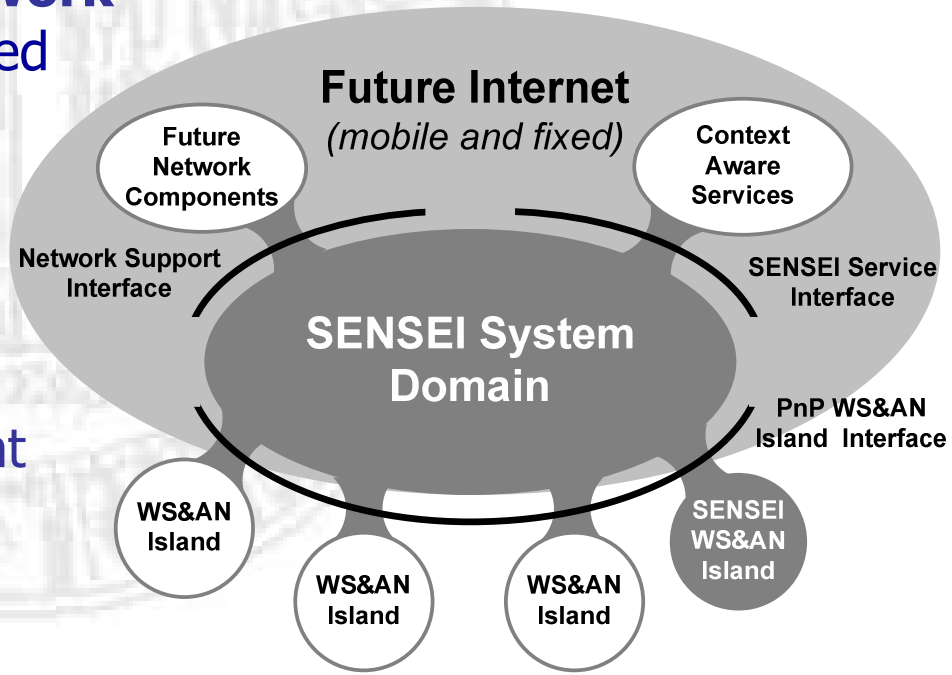
Key achievements of e-SENSE



- Assumptions and requirements
  - based on many application scenarios
- Definition of an end-to-end architecture
  - e-stack
  - From nodes to service platform
  - Gateway extensions and integration into IMS
  - Instantiated in specific use cases and tests
- Protocols, algorithms and mechanisms and protocol stack solutions:
  - **Energy efficient air-interfaces** for WSN achieving 20nJ/bit
  - **Innovative WSN communication mechanisms** tailored to the e-SENSE scenarios
  - **Cross-optimisation of protocol elements** and design of three WSN protocol stack instantiations for specific application scenarios
  - **Distributed services**, to address localisation, synchronisation and service discovery
  - **Distributed data processing** to support collaborative context awareness
  - An **integrated WSN middleware solution**, including service discovery, resource management and semantic transport middleware, based on a publish/subscribe model

WSANs in the Future Internet: SENSEI

- Objectives
  - **Integration of the physical with the digital world** to enable context-awareness for autonomous applications and services
  - Creation of an **open framework** for closed, vertically integrated wireless sensor and actuator networks (WSANs)
  - **Envision the design of the Future Internet**, as sensors and actuators will make up a very important part of it



SENSEI – key goals and expected outcomes

integrating the physical with the digital world of the network of the future

http://www.ict-sensei.org/ FP7 IP, ICT-215923

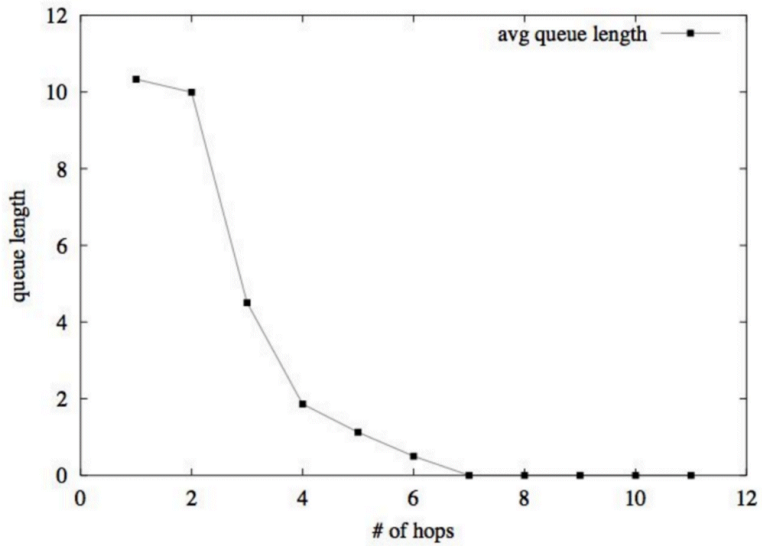
- A **highly scalable architectural framework** with corresponding protocol solutions that enable easy plug and play integration of a large number of distributed WSANs into a global system – providing support for network and information management, security, privacy and trust
- An **open service interface** and corresponding semantic specifications to unify the access to context information and actuation services offered by the system for services and applications.
- **Efficient WSANs island solutions** consisting of a set of cross-optimised and energy aware protocol stacks including an ultra low power multi-mode transceiver targeting 5nJ/bit.
- **Pan European test platform**, enabling large scale experimental evaluation of the SENSEI results and execution of field trials - providing a tool for long term evaluation of WSAN integration into the Future Internet.

Main technical issues for WSANs

- Self-configuration, fault-tolerance, adaptation, flexibility
- Energy efficiency
- Efficient protocol design and operation
- Scalability and heterogeneity
- Security, privacy and trust
- Architectural issues, interfacing with global system, interoperability with existing standard protocols
- Addressing, naming, localization, data-centric operation
- Mobility, delay tolerance
- Many applications, special- vs. general-purpose solutions
- Service creation and evolution, context representation
- Search engines based on physical attributes
- Advanced data handling, processing, dissemination (e.g., network coding or compressed sensing)
- Experimentation and demonstration of real and useful capabilities

Hot topic 1: cross-layer MAC/routing design

- Pros and cons of geographic routing protocols
  - Requires location estimation, dead ends must be dealt with
  - Stateless, local forwarding choices

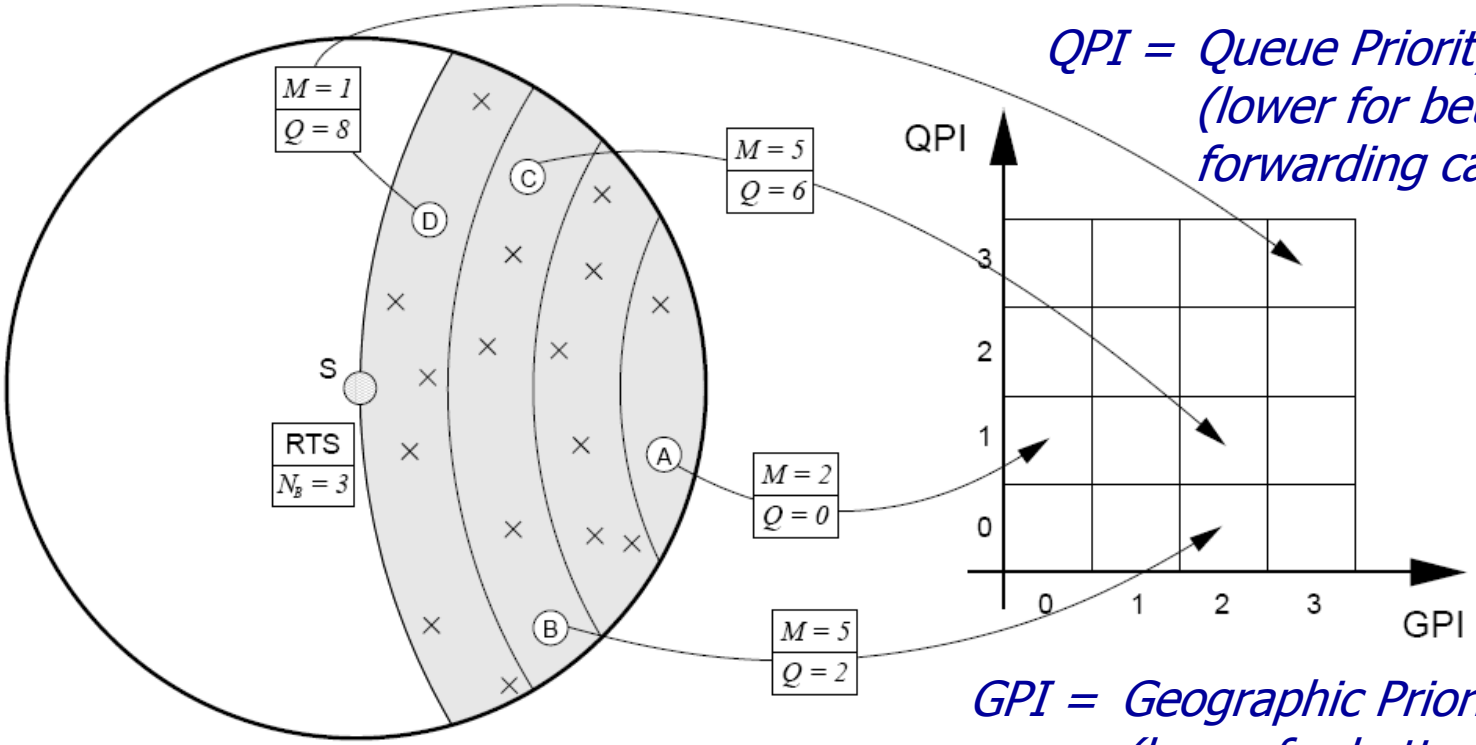


- Further problems with georouting
  - The advancement metric tends to concentrate traffic on "preferred" relays
  - When routing toward a sink, its neighbors get congested more quickly➔
- <u>A better algorithm should</u>
  - Choose uncongested relays that can actually forward packets
  - Balance between advancement and congestion at chosen relays
  - Use the channel efficiently when it is gained
    - ✓ Reduces the impact of signaling and sensing on protocol efficiency

ALBA – Our approach

- **ALBA ➔** Adaptive Load-Balancing Algorithm
  - Protocol for geographic forwarding in wireless sensor networks that balances the load among nodes using a hybrid metric
- Forwarders are elected based on
  - The geographic proximity to the destination
  - The ability to receive and correctly forward packets
    - ✓ The used metric involves both the transmitter requirements…
      - in terms of packets to transmit
    - ✓ …and the receiver's conditions
      - in terms of past forwarding history and estimated performance
- Operations:
  - Nodes forward packets in bursts (up to M_B packets back-to-back)
  - The length of the burst is adapted based on past memory

The hybrid ALBA metric



QPI = Queue Priority Index (lower for better forwarding capabilities)

GPI = Geographic Priority Index (lower for better progress)

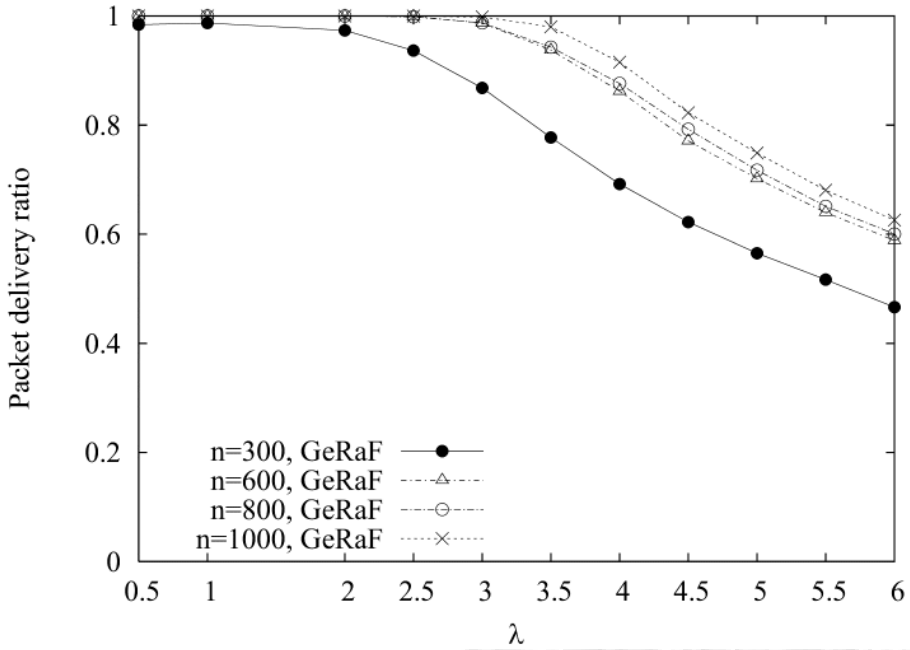
Queue level

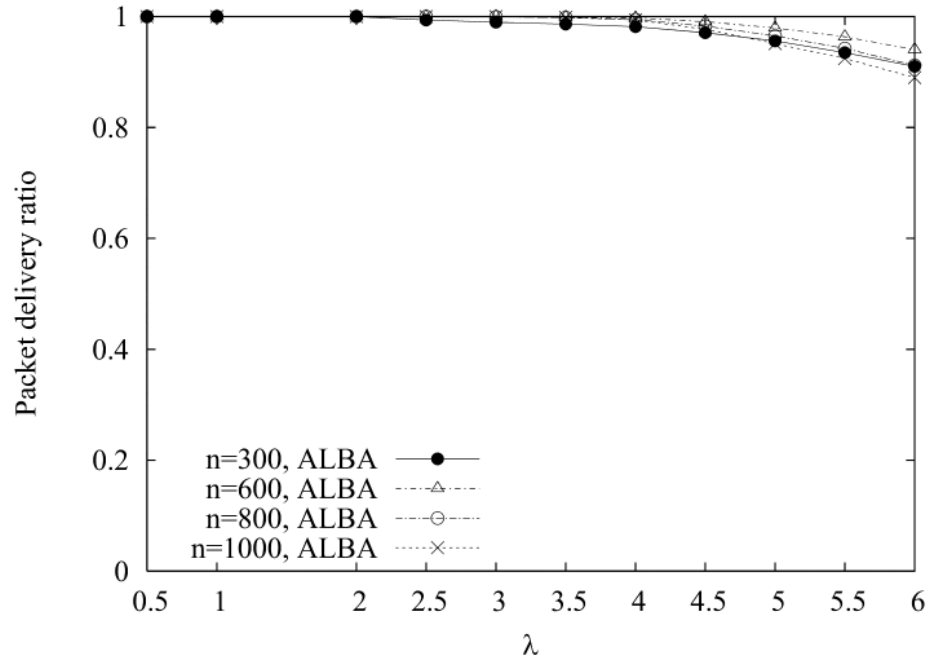
$$QPI = \lceil (Q + N_B) / M \rceil - 1$$

Requested length of the burst

Average length of a burst the relay expects to transmit correctly

ALBA vs. GeRaF: delivery ratio

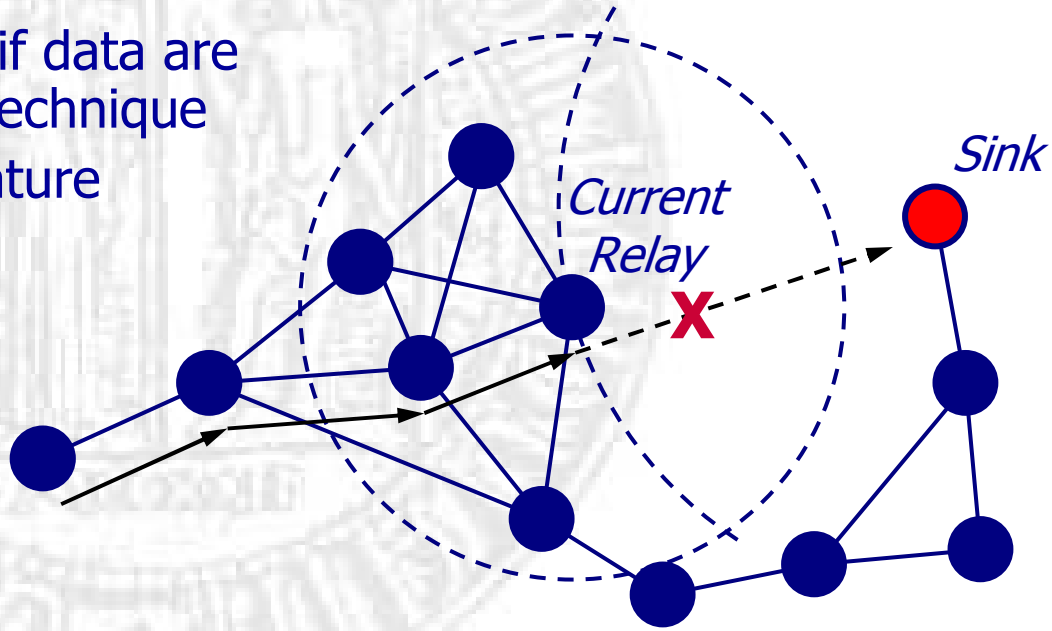




- Packets are dropped after too many unsuccessful attempts
- Percentage of packets delivered to the sink
- GeRaF lacks a load-balancing behavior
  - More congested nodes are chosen ➔ more packet dropping and backoffs
- ALBA effectively seeks advancement while preferring unloaded relays

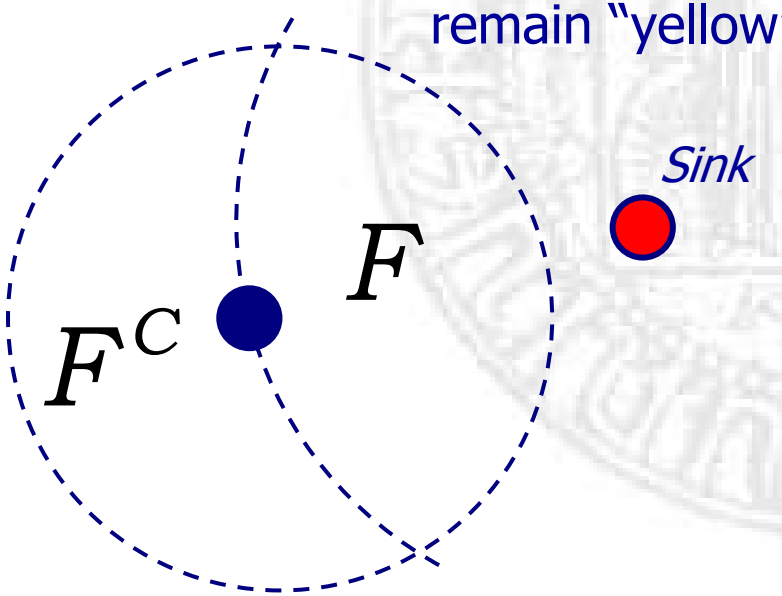
The dead-end problem

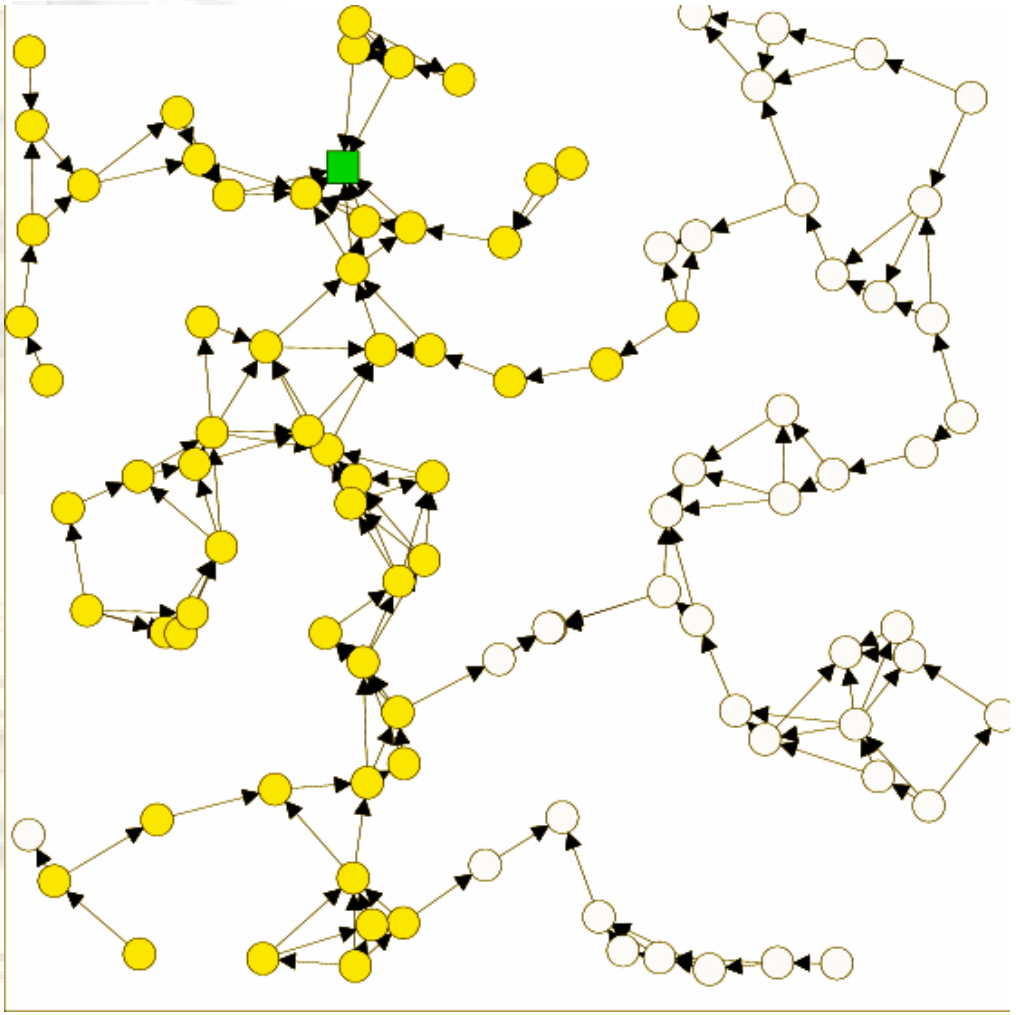
- Dead ends may be eventually reached in geographic routing
- In this example, a route to the sink is in fact available but the packets get stuck at the current relay (no nodes in the positive advancement area)
- Unavoidable packet losses if data are not re-routed using some technique
- Some solutions in the literature
  - Planarization
  - Tent + Boundhole: mark holes and locally cache circumventing paths
  - Full or partial flooding
  - Multi-path routing
  - Hybrid hole detection and resource management (e.g., nodes on boundary of holes route based on their residual energy)



Rainbow node coloring scheme – Yellow nodes

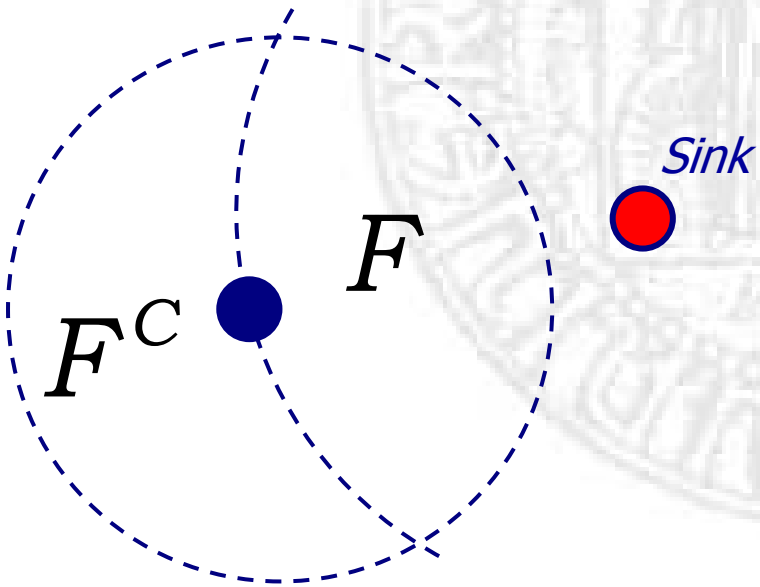
- F and F^C are the positive and negative advancement areas, respectively
- Initially, all nodes are "yellow"
- All nodes that have a greedy path to the sink remain "yellow"

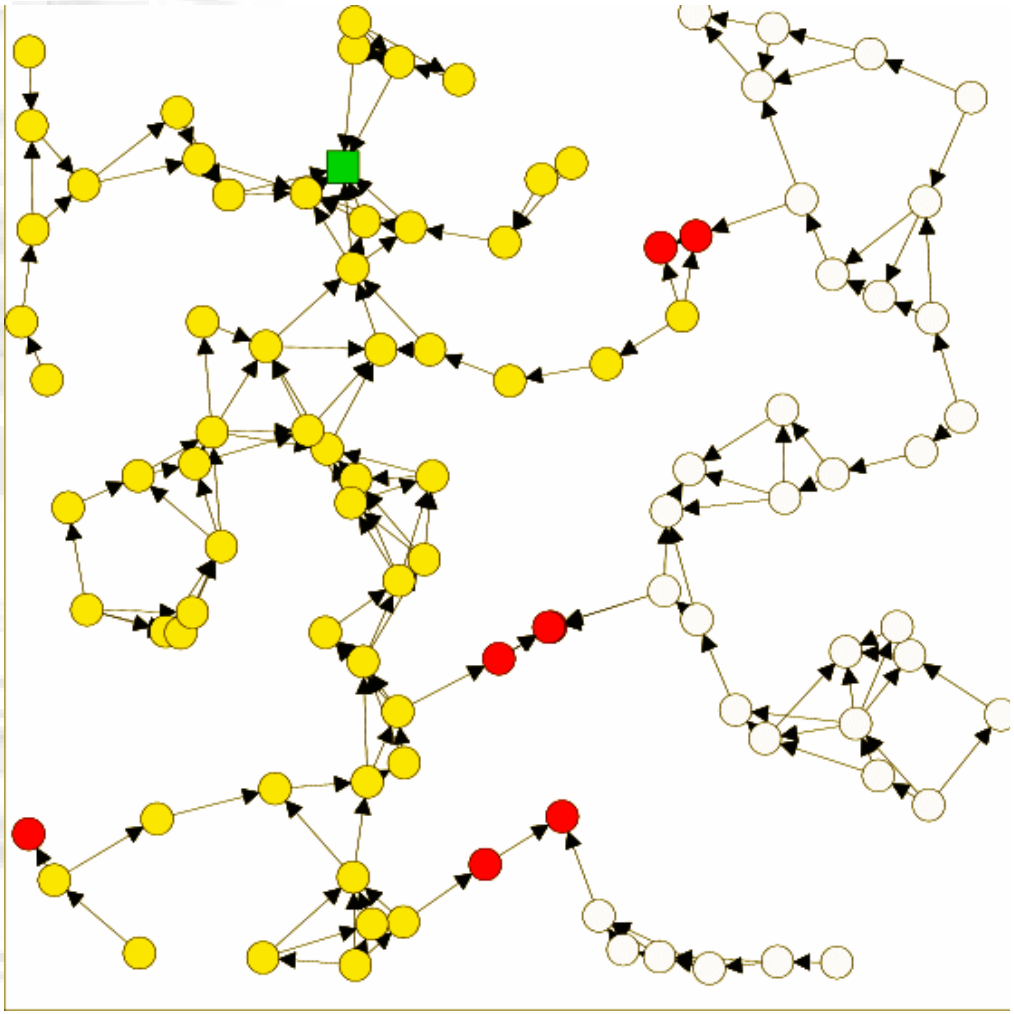




Rainbow node coloring scheme – Red nodes

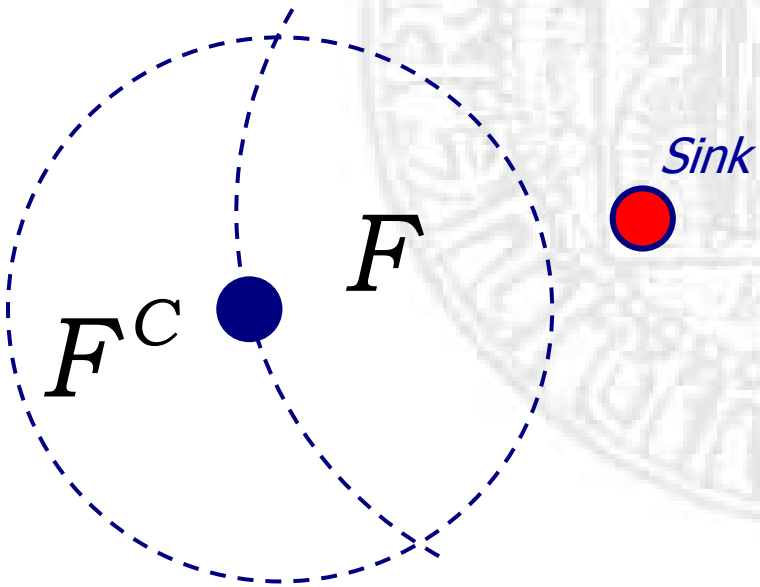
- If a yellow node cannot forward packets further, it switches to "red"
- From now, it looks for either "red" or "yellow" relays in F^C

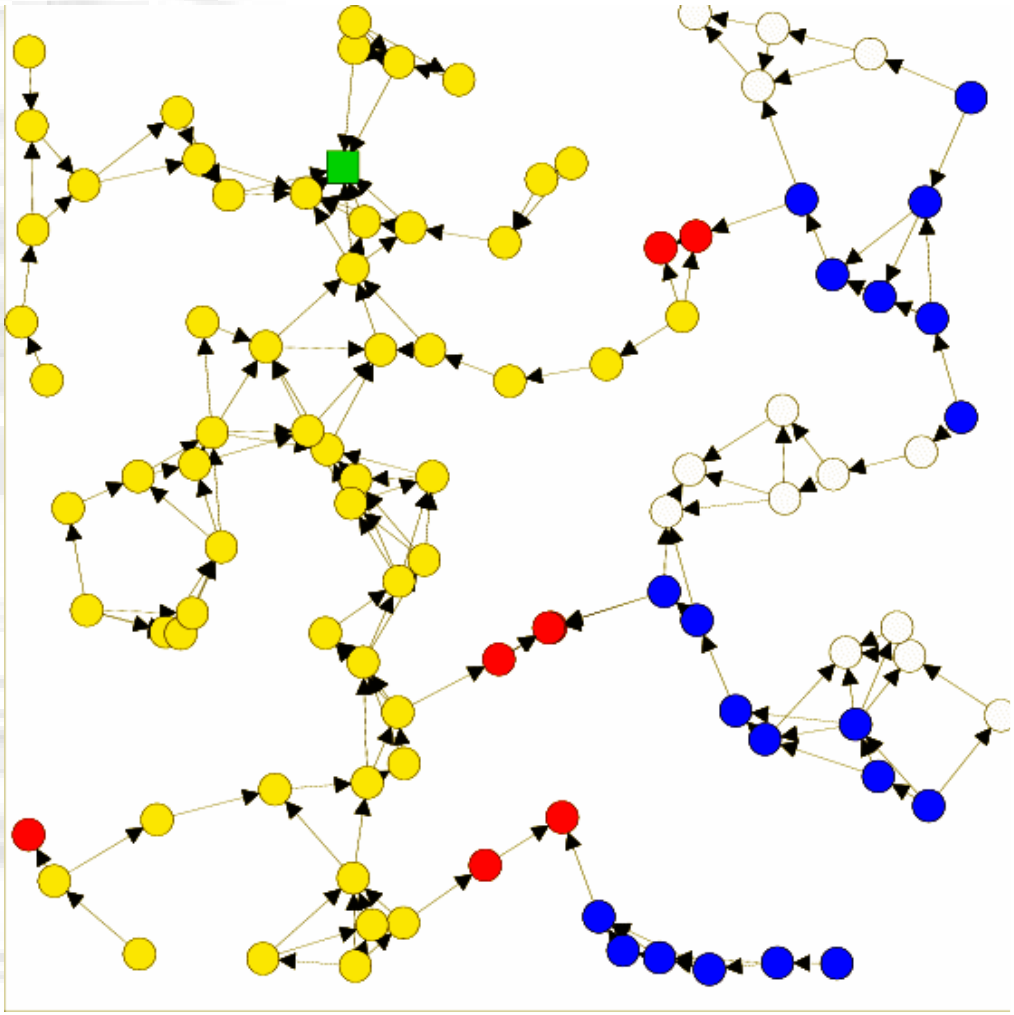




Rainbow node coloring scheme – Blue nodes

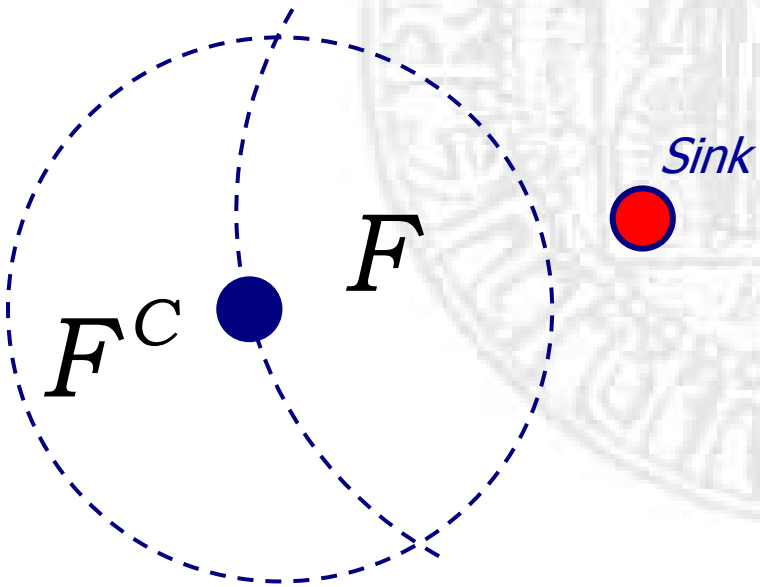
- If red nodes cannot advance packets, they turn to "blue"
- Again, they switch to look for relays in *F*
- They only look for "red" or "blue relays

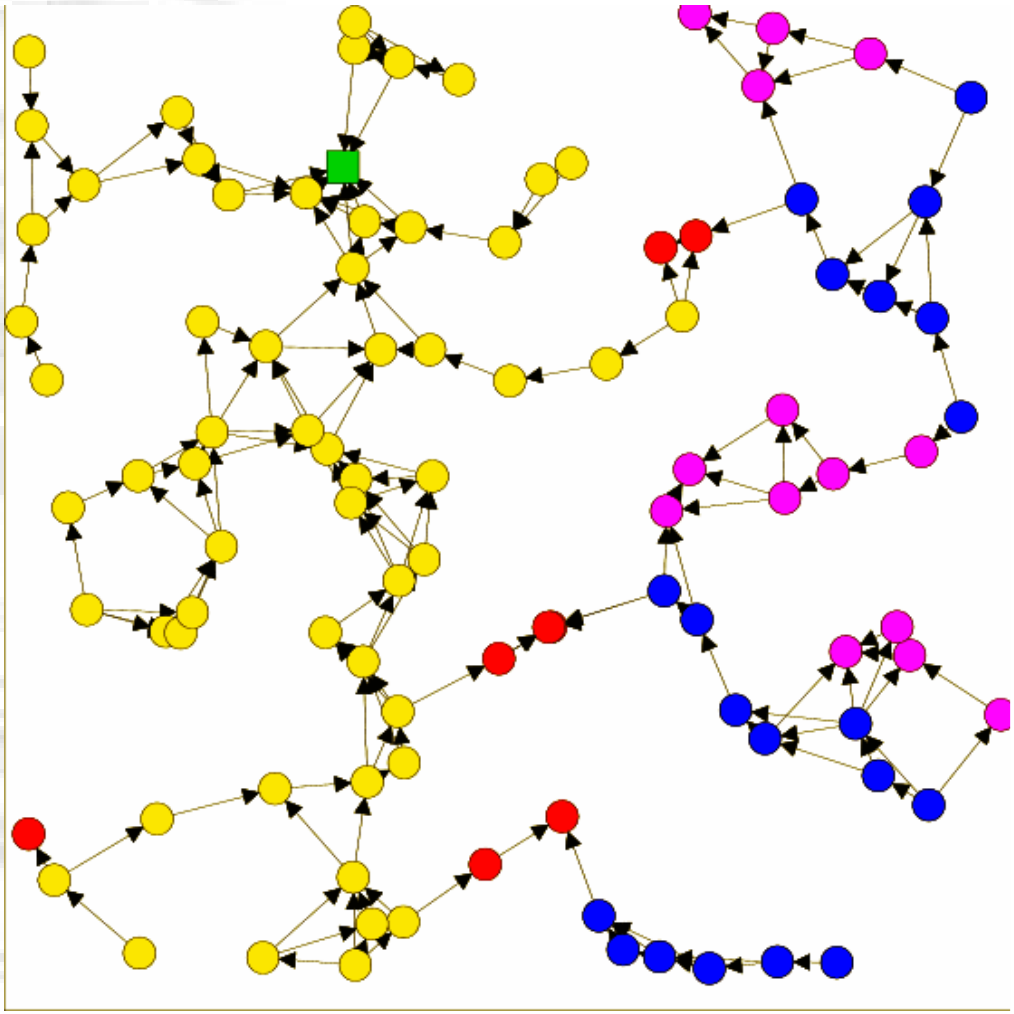




Rainbow node coloring scheme – Violet nodes

- If blue nodes still have problems finding relays they switch color again, to "violet"
- Like red nodes, they look for relays in F^C…
- …but only "blue" or "violet"



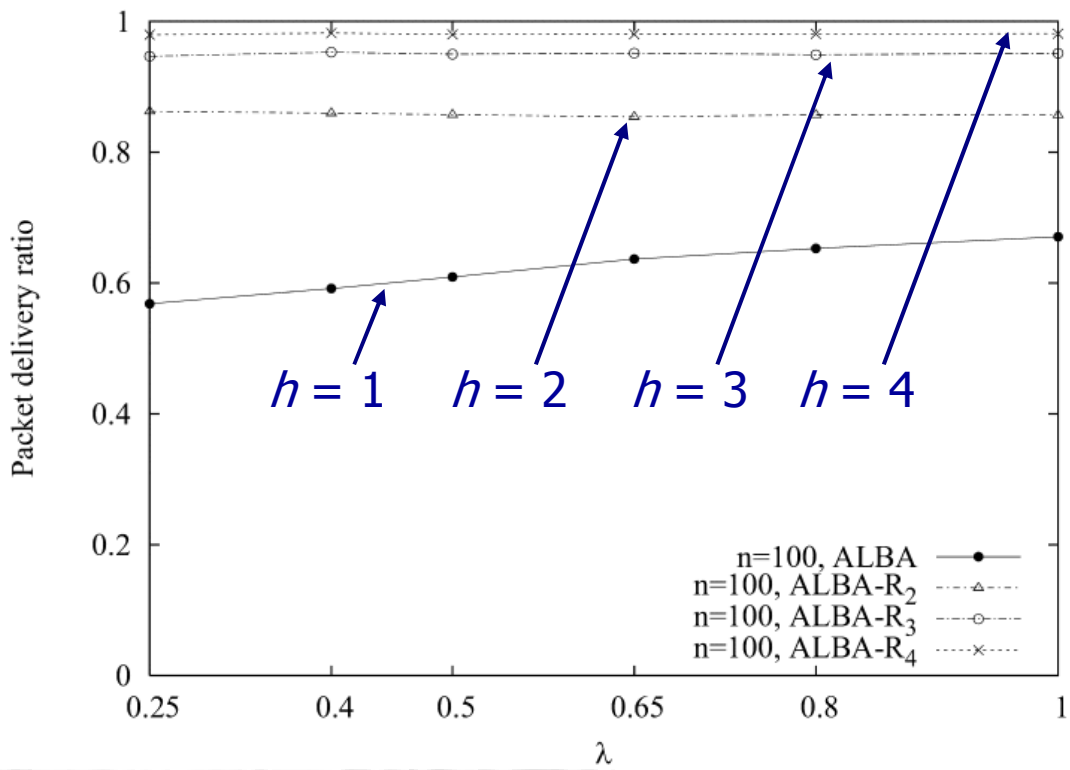


Rainbow – Low density – Delivery ratio (varying h)

- From: $h = 1$
  to: $h = 4$ colors

- Increasing the number of colors connects more nodes to the converge-casting tree

- The average delivery ratio increases

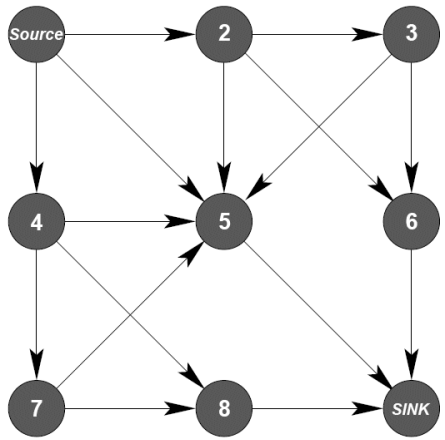


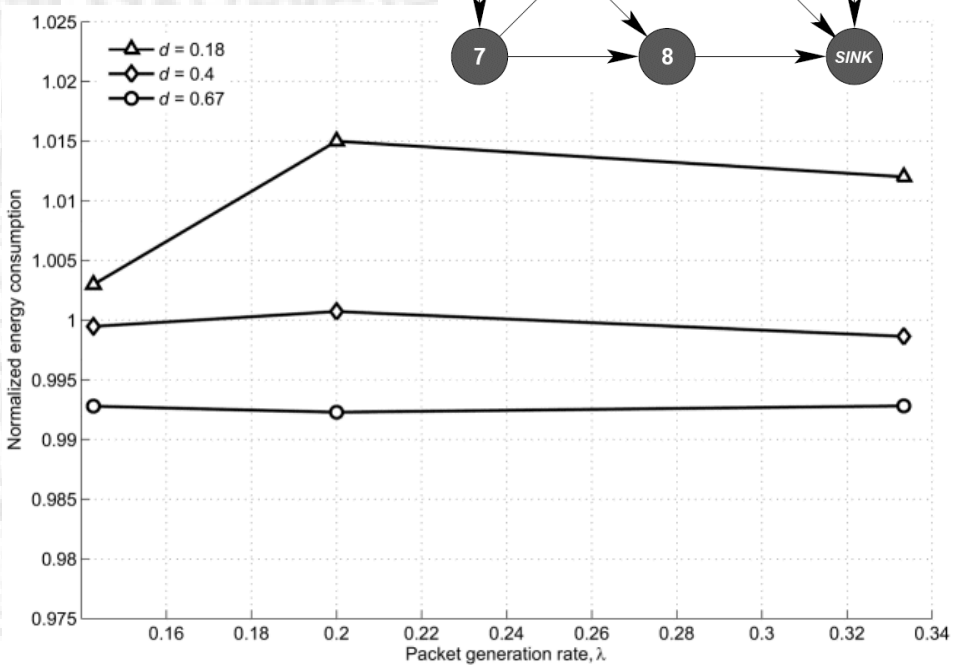
- Note: after all nodes are connected with the used number of colors, the residual errors are due to packet losses caused by channel impairments or by the difficulty to find relays
- For more info, check our paper in IEEE ICC07 (Casari et al.) and its refs

Preliminary experiments with real motes

- We have implemented ALBA on EyesIFXv2 nodes
- We ran tests for three different traffic and duty cycle values
  - λ = 1/7, 1/5, 1/3 pkts/sec
  - d = 0.18, 0.4, 0.67
- Objective: measure energy consumption and compare to plain duty-cycling

- Observations
  - ALBA is very lightweight (albeit only one source here)
  - Values in accordance with sims (e.g., 1.014 vs 1.012 at d = 0.18, λ = 1/3)





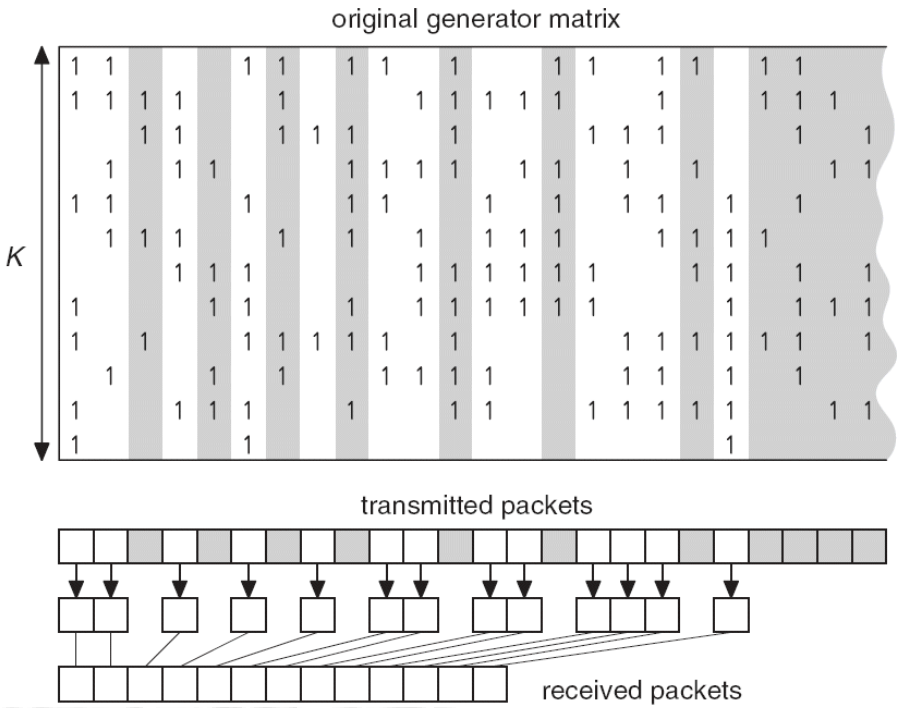
Hot topic 2: Wireless Reprogramming

- Wireless reprogramming is a key application in any WSN deployment
  - Useful for software updates, or simply to run different experiments
  - Programming many nodes through USB is impractical
- Usually done through flooding or similar broadcasting techniques
  - Deluge (earliest dissemination)
  - MNP (ADV/REQ phase with reduced collisions)
  - Freshet (introduces sleep modes)
  - All based on plain ARQ, ADV/REQ, and some kind of flooding
- Our SIGNET group in Padova is currently investigating more efficient methods to spread information in a WSN
- SYNAPSE
  - A wireless reprogramming application based on Fountain Codes
  - Fountain Codes allow a more efficient form of Hybrid ARQ
  - More degrees of freedom: optimize for overhead, computation, or both?

Fountain Code basics

- Fountain codes are rateless
  - K packets to transmit
  - Extract n vectors, each with K random bits (0 or 1)
  - XOR only the data packets s_k with a corresponding 1 in the random vector

$$t_n = \sum_{k=1}^{K} s_k G_{kn}$$

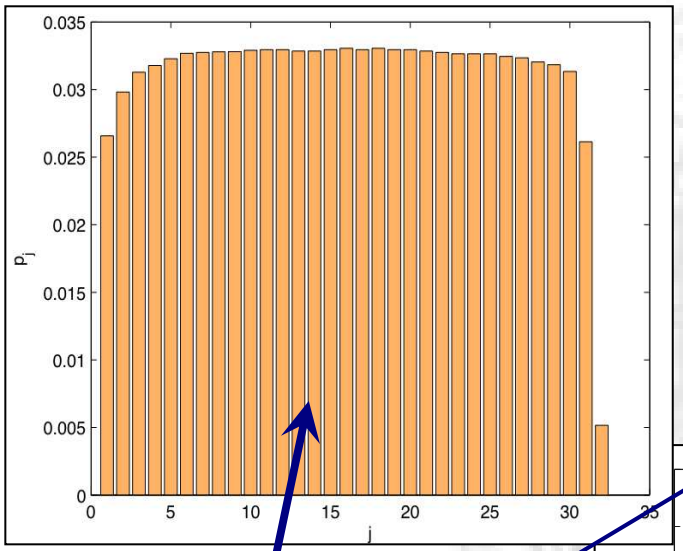


  - Send any number n of packets generated this way (ratelessness)
  - Decode using, e.g., Gaussian elimination
  - Pro: rateless
  - Con: requires K(1+ε) packets to recover K even if no errors

$$s_k = \sum_{n=1}^{N} t_n G_{nk}^{-1}$$

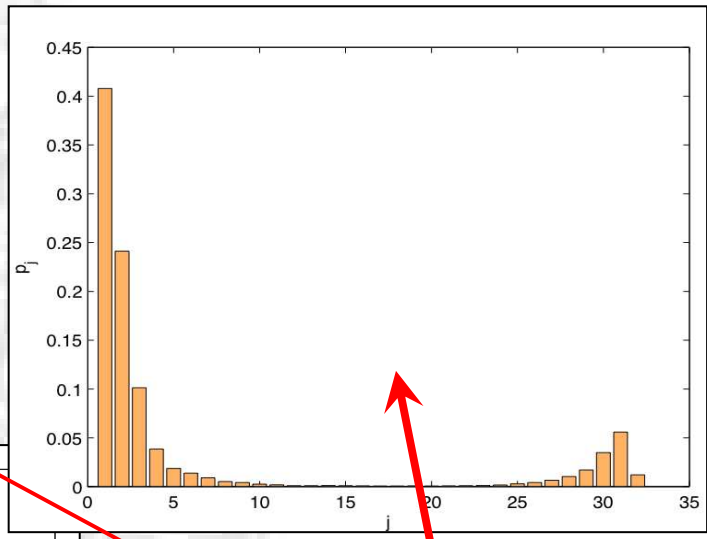
Which degree distributions?

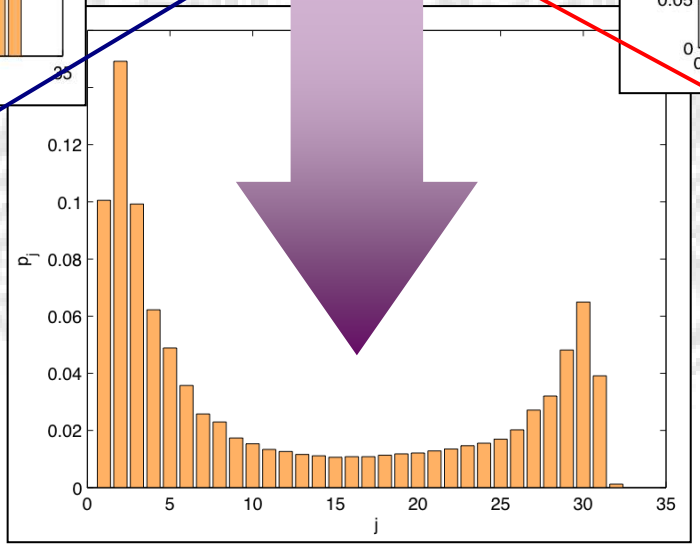
- The degree is the number of source packets XOR'ed to form a coded packet



← High degrees:
← more likely to invert

Low degrees: →
less computation →



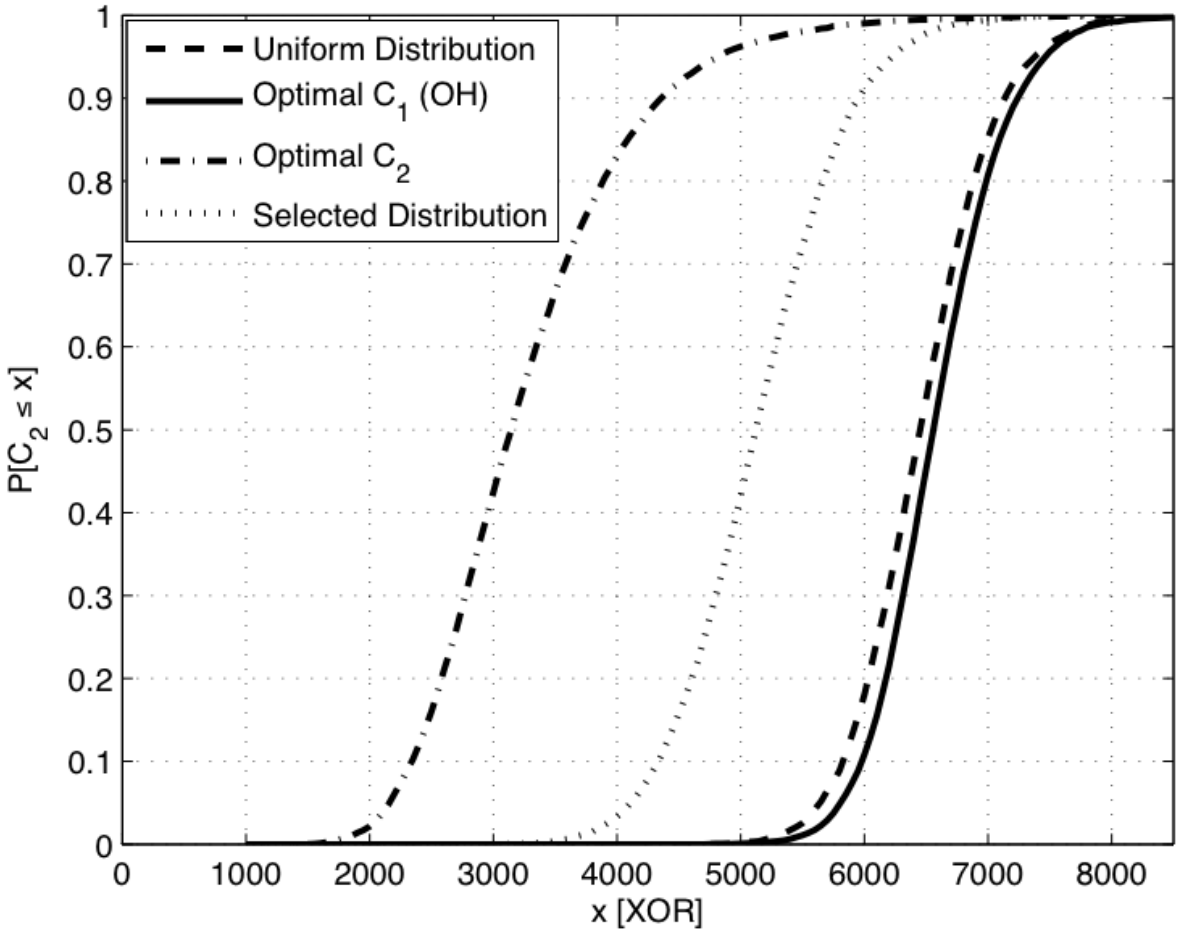


Optimized for overhead

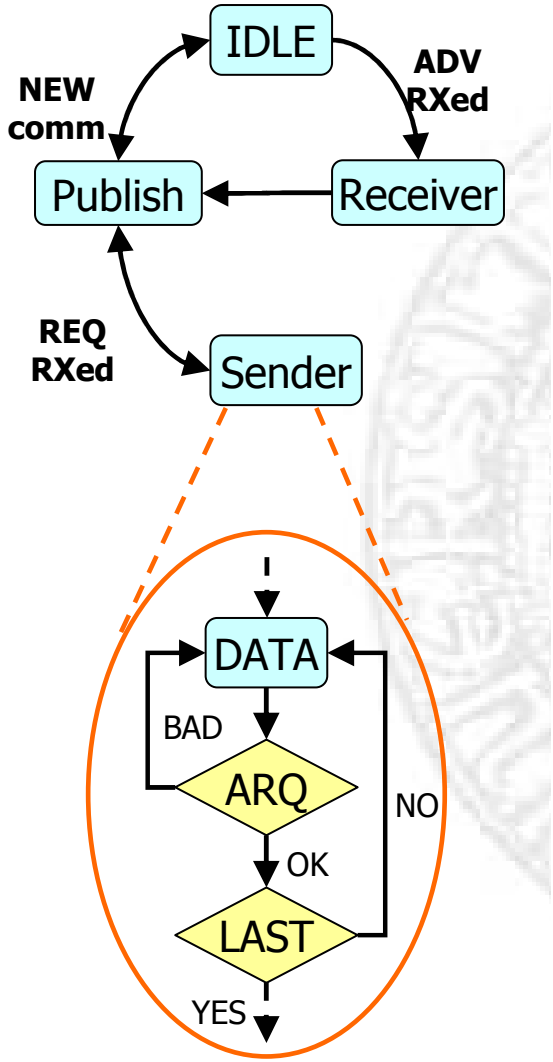
Optimized for decoding speed

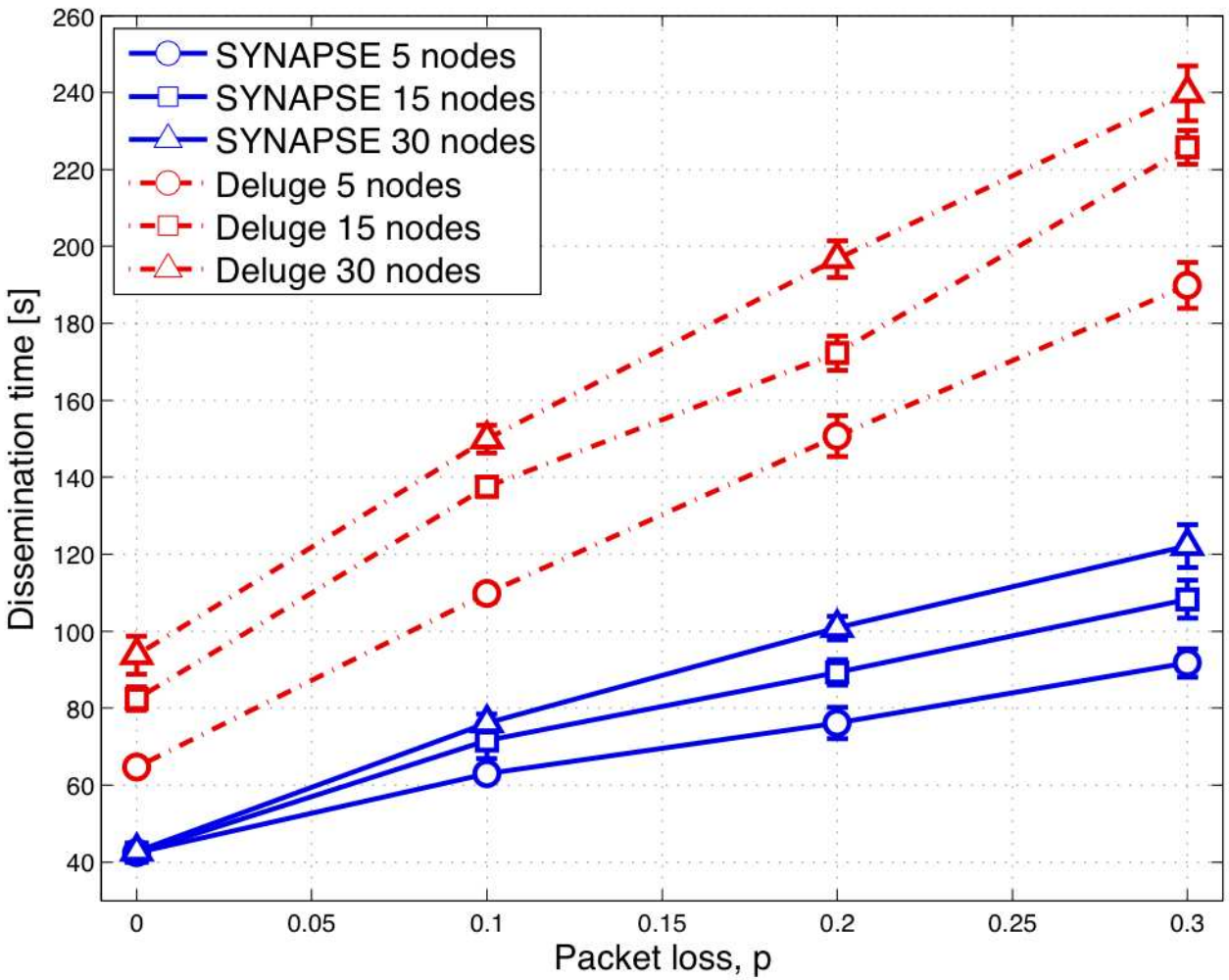
Cost comparison of different distributions

- Cost defined as number of XORs to get packets decoded

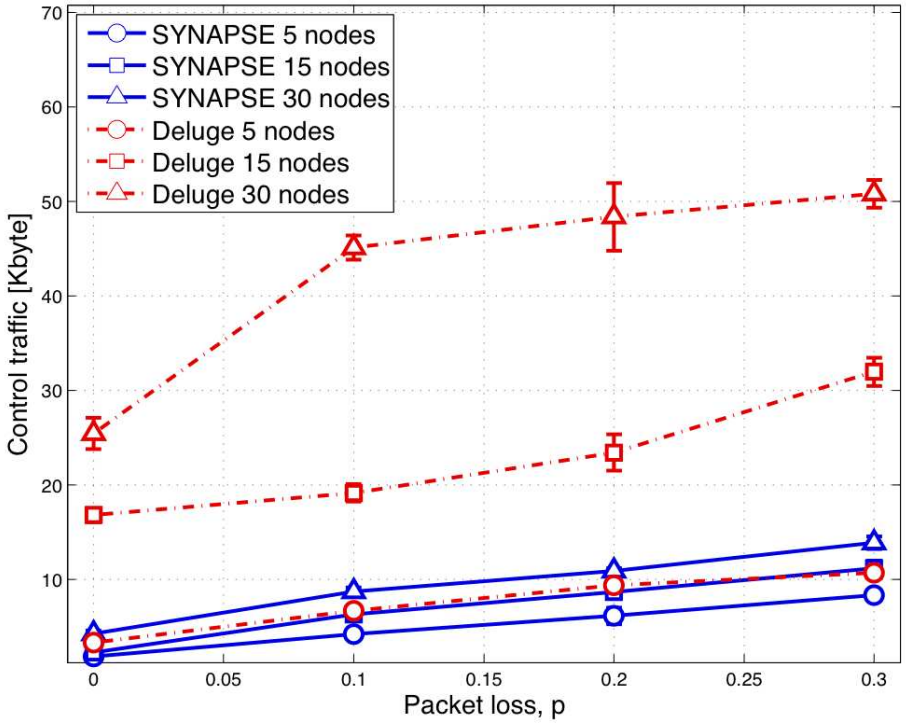


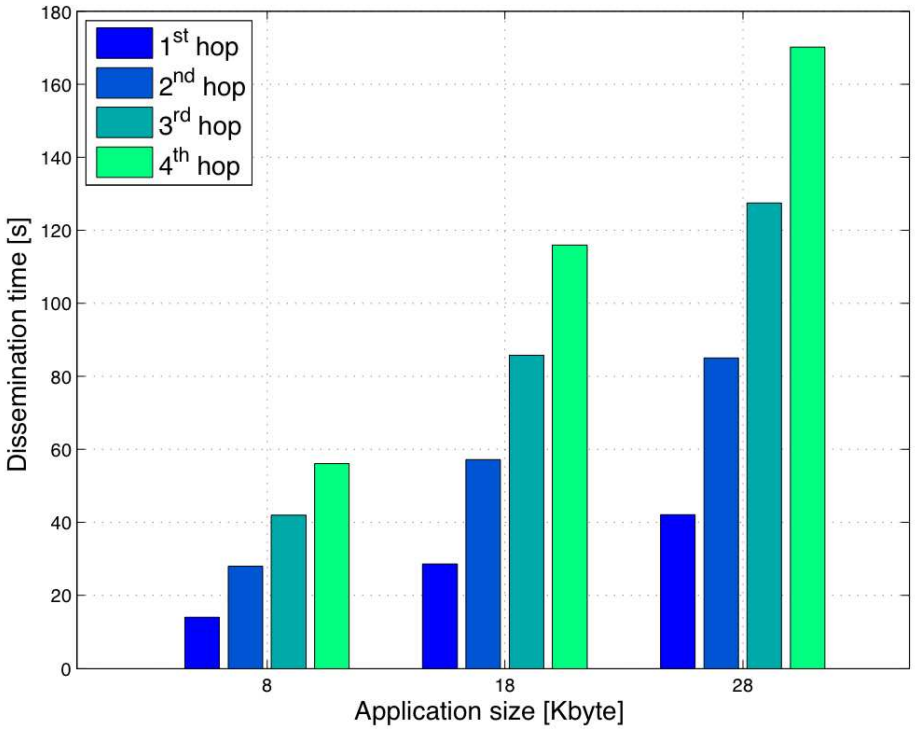
SYNAPSE state chart and one-hop dissemination time





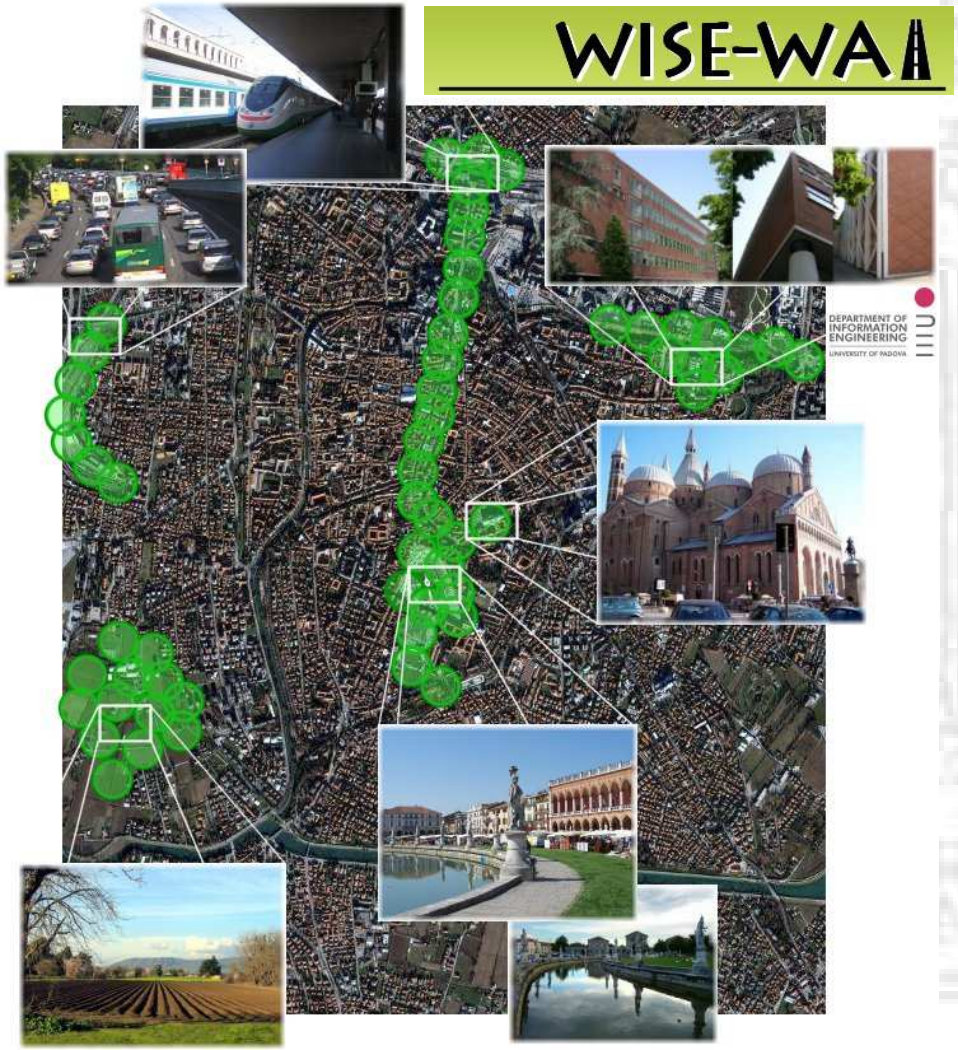
Overhead and multihop performance





- Both dissemination time and overhead consistently outperform deluge
- Dissemination time linear in number of hops and application size
- Effective error recovery: new overhead packets are useful to any unsuccessful receiver, not just those that requested more redundancy
- For more info check our SYNAPSE paper at IEEE SECON2008

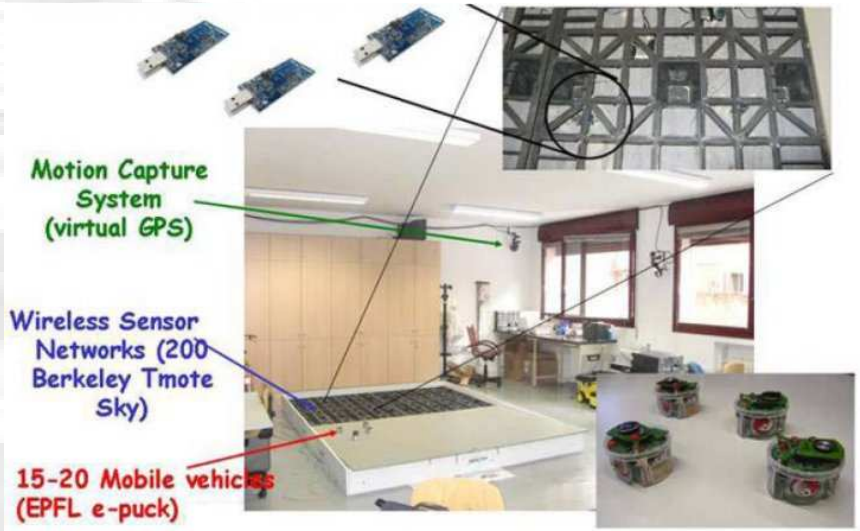
The WISE-WAI Project



- The research undertaken at SIGNET is being exploited within the framework of a 3-year project, WISE-WAI
- The objective of the project is to blend expertise in hardware design, communications, networking, automatic control and applications
- Among the target outcomes, there will be a building complex-wide testbed (first) that will be eventually extended to a city-wide scope
- We aim at making the testbed data and capabilities accessible to the community through our website
- This will allow to turn research concepts into real context-aware applications, services and ambient intelligence
- Web site ➔ http://cariparo.dei.unipd.it

Testbed specifications

SignetLab testbed



SensNet testbed

- We will start from the two testbeds already deployed inside 2 buildings of the DEI complex in Padova
- Both networks will be extended in steps
  - First step will yield full coverage of the buildings where the labs are located
  - Second step will extend the network and bridge different wireless technologies
  - Last step will estend the network to a wider territory and provide remote control tools

Technical issues for testbed deployments

- Cables (e.g., USB, used to power and program nodes as well as to retrieve data and experiment logs)
- Development of a simple (e.g., web-based) interface to program nodes and run experiments
- Battery duration for non–cabled nodes

- These issues are increased in case of
  - Large numbers of nodes (100-1000)
  - Heterogeneous technologies (different sensor boards, wi-fi, bluetooth…)
  - Harsh environment (e.g., industrial, high-interference …)
  - Indoor connectivity in large building complexes
  - Diverse traffic requirements (monitoring, event response …)

Testbed under construction at University of Padova

- More than 300 nodes over a large area of thousands of m^2
  - Mainly indoor (highly attenuating and time-varying channel)

- Hybrid technologies
  - Will embed Eyes, Tmotes, 802.11a/g/n, zigbee, bluetooth, requiring explicit bridging among these technologies
- Fully remote network control
  - Data harvesting, logging and configuration via remote connections
  - Wireless node reprogramming
- Adaptive support to diverse applications
  - Environmental sensing/control, alarm, query and event response

Conclusions

- Wireless sensor networks have become part of our networked world and their importance will tremendously grow
- While born as stand-alone systems for monitoring and surveillance, they are evolving into a key component of next generation networks and the future internet
- Bridging the gap between digital and physical world
- Context, ambient intelligence, and service creation platforms
- Heterogeneity and scalability will play a key role
- Actuation, in addition to sensing, is becoming more and more important
- "Traditional" solutions developed in the past few years have not adequately addressed this new reality
- Many technical issues are still to be fully addressed and solved
- Successful approaches require advanced paradigms, interdisciplinary expertise, cross-layer solutions
- Despite the large amount of existing work, WSANs remain an exciting and open field of research