Wireless Mesh Networks

Part 2: Technologies, Case Study TOWN

Eduard Glatz (eglatz@hsr.ch)

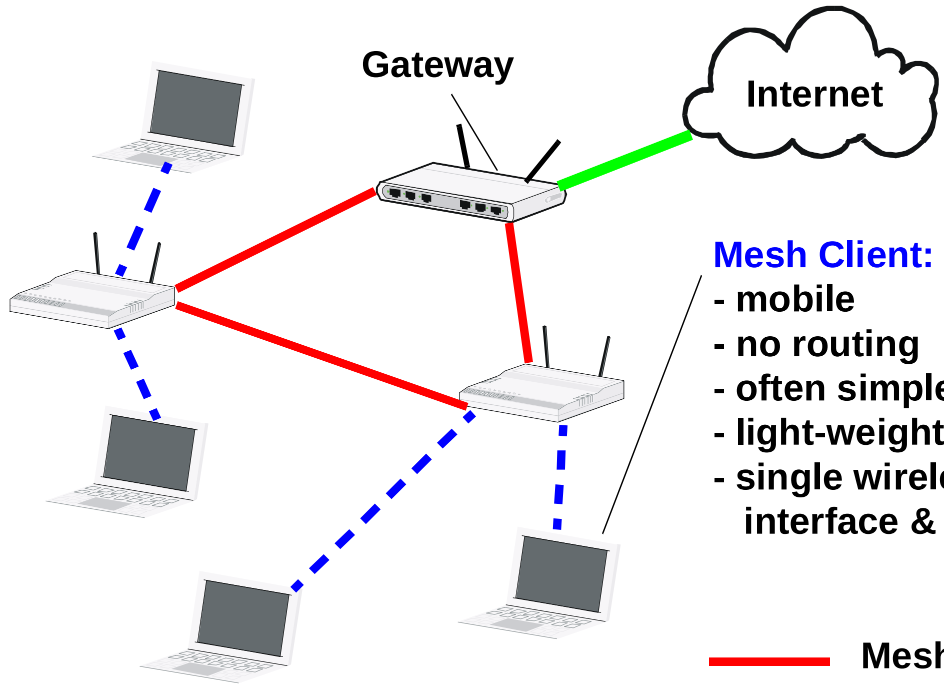
Summarizing the last lecture on Wireless Mesh Networks

A WMN is dynamically *self-organized* and *self-configured*:

- Nodes in the net establish automatically an ad-hoc network
- Nodes maintain the mesh connectivity

Two types of nodes: mesh routers & mesh clients

Mesh Router:
- stationary
- often bridge/gateway
- often multiple interfaces (same or different technologies, wired & wireless)
- often multiple radios & antennas
- complex software



Mesh Client:
- mobile
- no routing
- often simple hardware
- light-weight software
- single wireless interface & radio

Mesh network

Motivation for Wireless Mesh Networks

Wireless mesh idea dates back to ~1995 but is still not fully explored

Mesh idea is not tied to a particular wireless technology

Mesh networks are:

- Decentralized
- Relatively inexpensive
- Reliable and resilient

Wireless mesh networks are a subclass of ad-hoc networking

Agenda

Introduction

- Wireless coverage
- Wireless mesh network architectures

Technologies

- IEEE 802.11, 802.16 and 802.15

Case Study: TOWN Project

- Application scenario
- Requirements and constraints
- Topology construction
- Channel allocation

Summary

Objectives

You can list three technologies suitable to form WMN's and explain their differences in medium access control and supported topologies.

You can describe three major problems to be solved when implementing a well performing WMN.

You can demonstrate the use of graph theory to model connectivity and interference conflicts in a WMN.

You can describe and evalute practical approaches to infer a connectivity graph and an interference conflict graph for a real-world WMN.

You can explain two algorithms for topology construction of a static backbone WMN.

You can explain at least one algorithm for channel allocation in a WMN.

You can give four evaluation criteria assess simulations of wireless mesh networks.

Introduction: Wireless Coverage

We know: SNR value is key
- SNR threshold limits range
- Adaptive modulation/coding supports range/capacity tradeoff

SNR Calculation in a Nutshell

$$SNR[dB] = P_r[dBm] - N[dBm]$$

$$N[dBm] = -174 + 10 \cdot log(f_{bw}) + NF$$

$$P_r[dBm] = P_t[dBm] - L_{fs}[dB] + G_t[dBi] + G_r[dBi]$$

$$L_{fs}[dB] = n \cdot 10 \cdot log\left(\frac{4\pi df}{c}\right)[dB]$$

P_r: Received signal power
N: Noise
f_{bw}: Bandwidth [Hz]
NF: Noise figure
P_t: Transmit signal power
L_{fs}: Free space loss
G_t, G_r: Gain of tx/rx antenna
n: path loss exponent (see table)
d: Distance between antennas
f: Frequency
c: Speed of light

Free Space	Urban	Suburban	Indoor LOS	Indoor NLOS
n = 2	n = 2.7 - 3.5	n = 3 - 5	1.6 - 1.8 (?!)	n = 2 - 6

Values for wireless channels (frequency range: 3 - 30 GHz)
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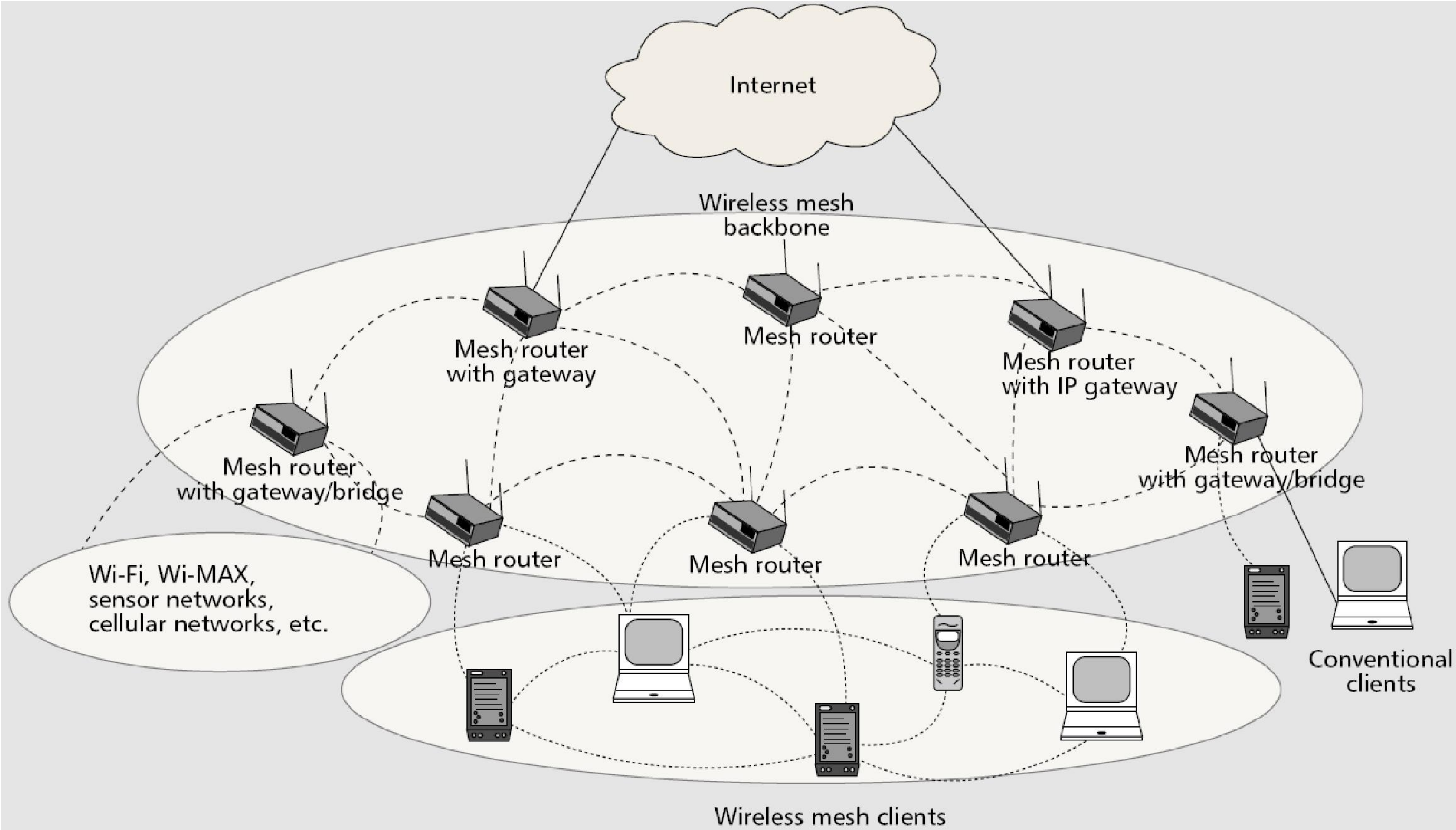
Introduction: Wireless Mesh Network Architecture



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Infrastructure/Backbone WMN

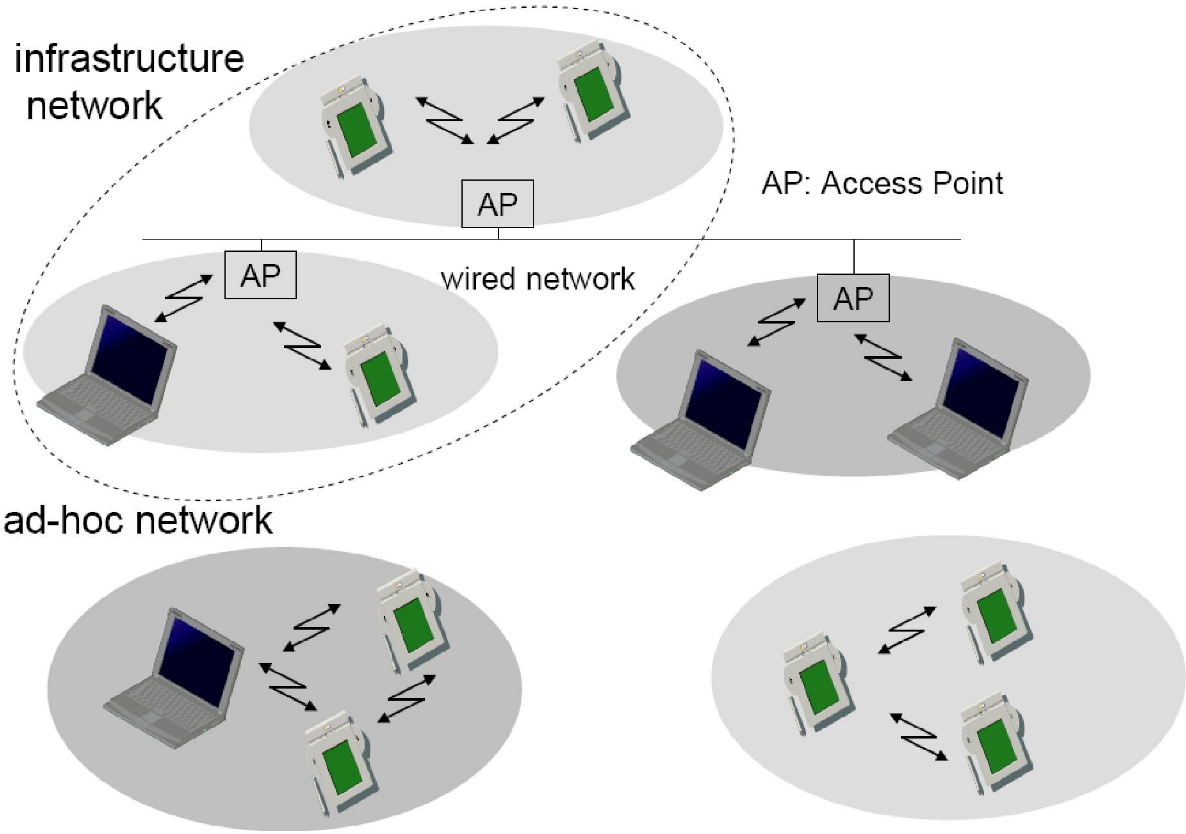
Client WMN

Hybrid WMN (shown above)

Technologies: 802.11 Wi-Fi (WLAN)

Based on IEEE 802.11 standard: several variants exist, more are evolving

Wi-Fi: brand confirms compliance to interoperability standards (WiFi forum)



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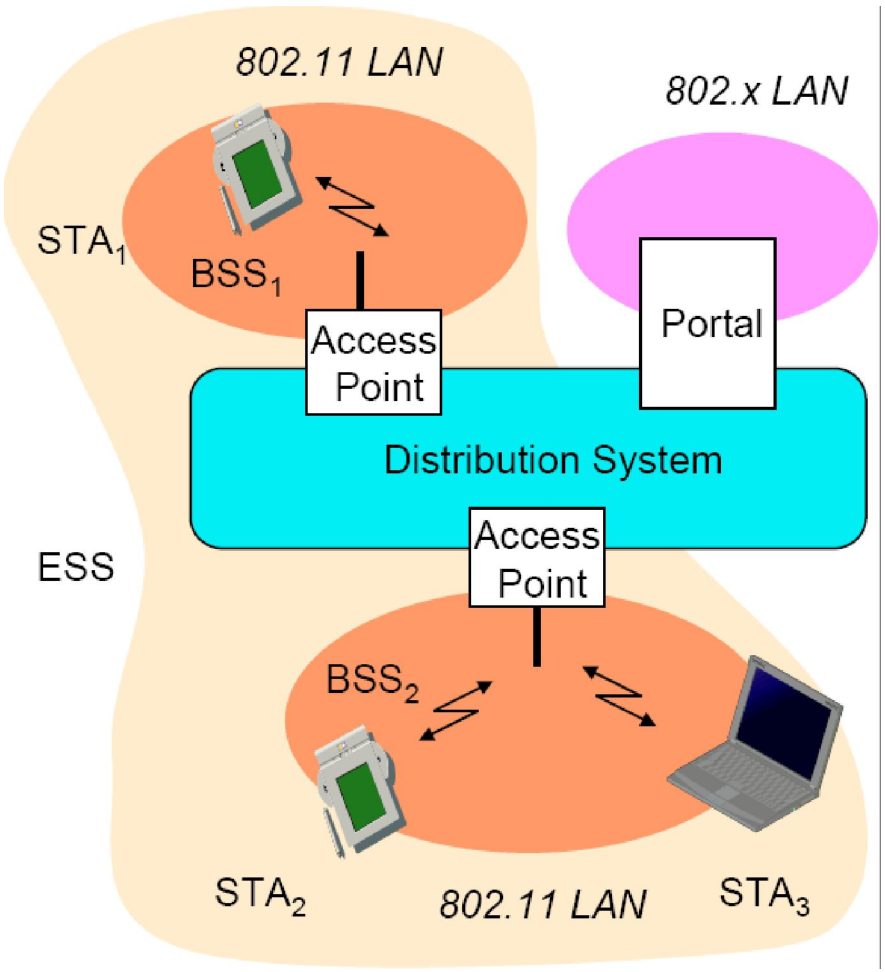
Topologies:
- ad-hoc
- infrastructure

Popular:
- PC P2P connectivity
- wireless infrastructure

Capacity/range tradeoff:
- Adaptive modulation

Technologies: 802.11 Network Architectures

Infrastructure Network



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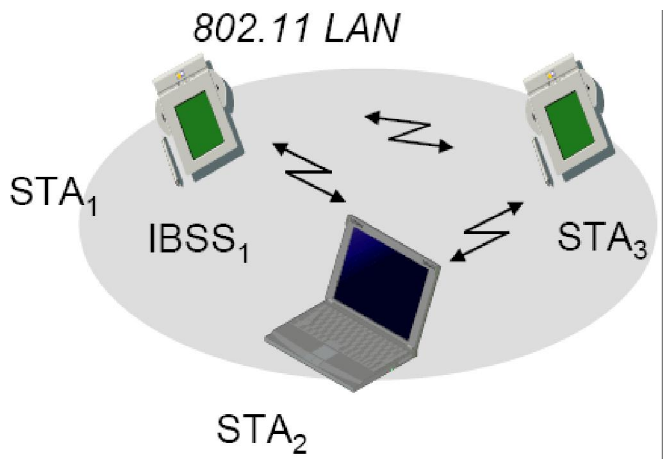
Terminology:
- STA (Station)
- AP (Access Point)
- BSS (Basic Service Set)
- Portal
- Distribution System
- ESS (Extended Service Set)
- IBSS (Independent BSS)

Ad-hoc Network



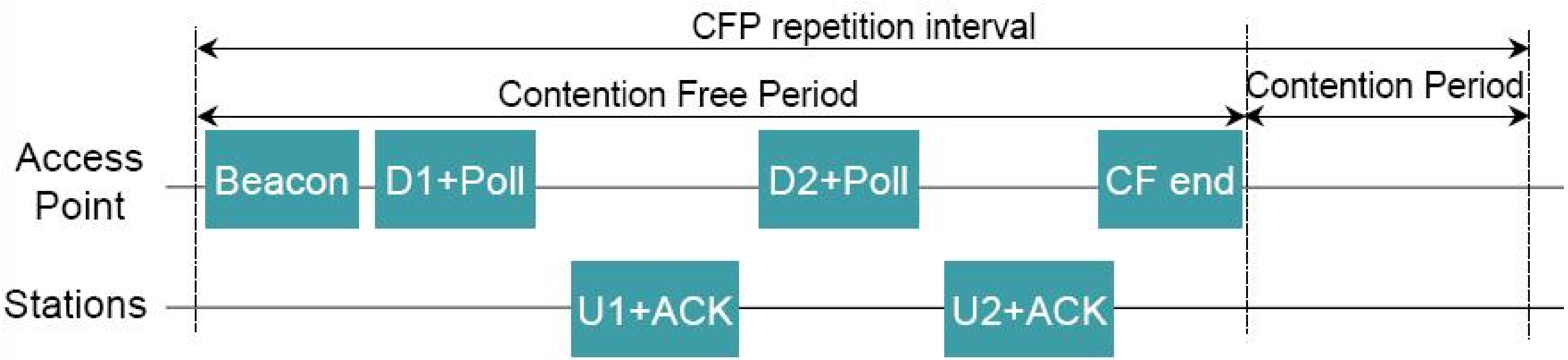
Technologies: 802.11 Medium Access Control (MAC)

DCF (Distributed Coordination Function) is basic medium (channel) access control

- Ad-hoc networking
- CSMA/CA
- RTS/CTS + ACK (=MACAW) with MAC level recovery (retransmission)

PCF (Point Coordination Function) as an option:

- Access point (infrastructure mode)
- Alternates between *contention free period* and *contention period* (under control of AP)
- AP polls stations for data during contention free period
- Improves QoS for time bounded data



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Technologies: 802.16 WiMAX Technology (WMAN)

Based on IEEE 802.16-2004 standard:

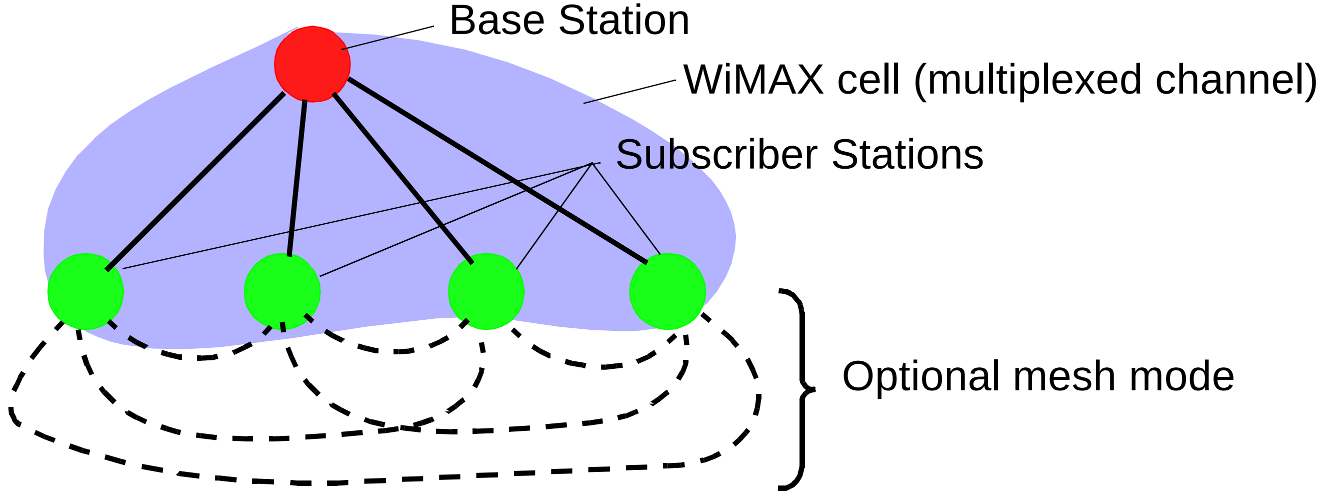
- Basic systems are stationary
- Mobility extension 802.16e

WiMAX (Worldwide Interoperability for Microwave Acces):

- Label for 802.16 systems promoted by WiMAX forum
- Certified products are guaranteed to be interoperable

Wider coverage compared with 802.11 (1 .. 66 km)

Basic topology: Point-to-Multipoint (PMP)



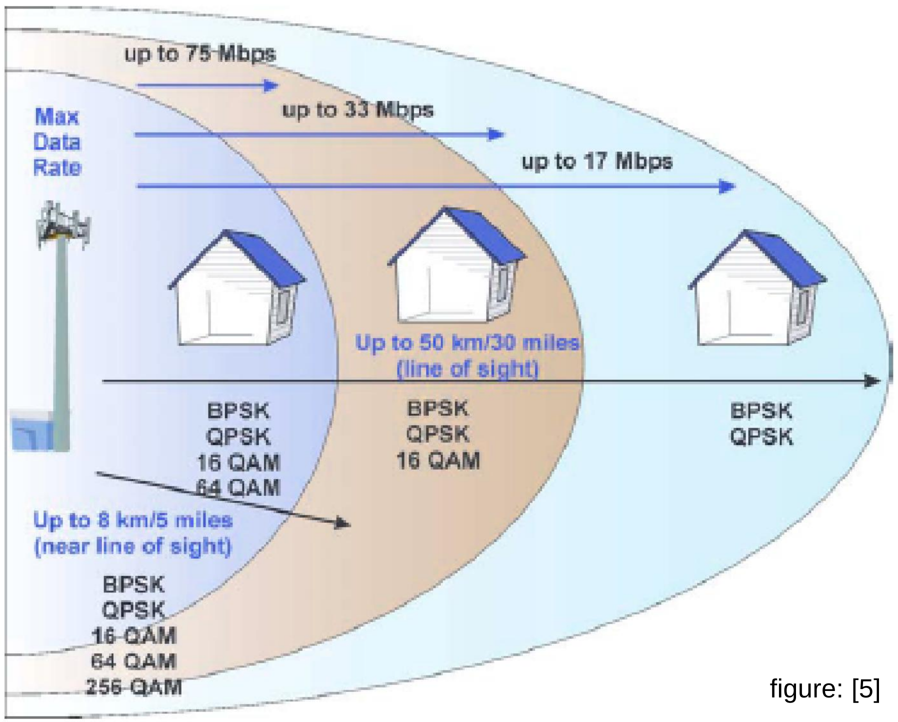
Specialized topology: Point-to-Point combined with parabolic antennas (long distance)

Technologies: 802.16 MAC and PHY Layer

Dynamic TDMA (Time Division Multiple Access) as medium access control

TDD (Time Division Duplexing) for uplink/downlink in unlicensed frequency bands

Capacity/range tradeoff: adaptive modulation and coding



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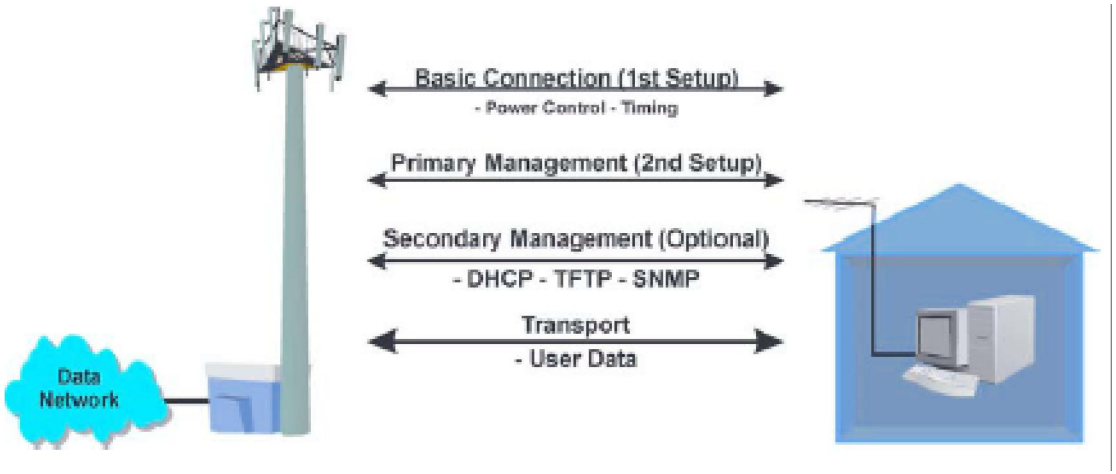
Transmit power control:
- BS adjusts tx power of SS (by use of MAC management PDU‘s)
- Goal 1: same receive power at BS for all SS
- Goal 2: decrease interference and power consumption

Technologies: 802.16 QoS (Quality-of-Service)

Connection-oriented MAC layer: supports individual QoS level per data stream



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- 3 management connections
- 0 or more service flows (may utilize different QoS classes)
- Managed QoS on a per-connection basis
- 4 QoS classes: Best Effort (BE), non-real-time Polling Service (nrtPS), real-time Polling Service (rtPS), Unsolicited Grant Service (UGS)

Technologies: 802.15 Bluetooth (WPAN)

Primary purpose is to connect mobile phones & PC‘s with accessories

Short range communication: 3 classes using different transmit power

- class 1: 100 mW, approximate range 100 m
- class 2: 2.5 mW, approximate range 100 m
- class 3: 1 mW, approximate range 1 m (most popular)

FHSS (Frequency Hopping Spread Spectrum): 1600 hops/s, 79 frequencies

TDMA as medium access control

Maximal data rate is 3 Mbps (Bluetooth 2.0)

Future: UWB (Ultra-Wide-Band) with up to 480 Mbps

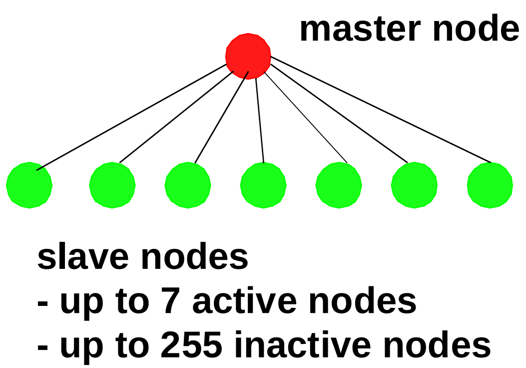
Technologies: 802.15 Bluetooth (WPAN)

Often but not necessarily all nodes are inside each others communication range

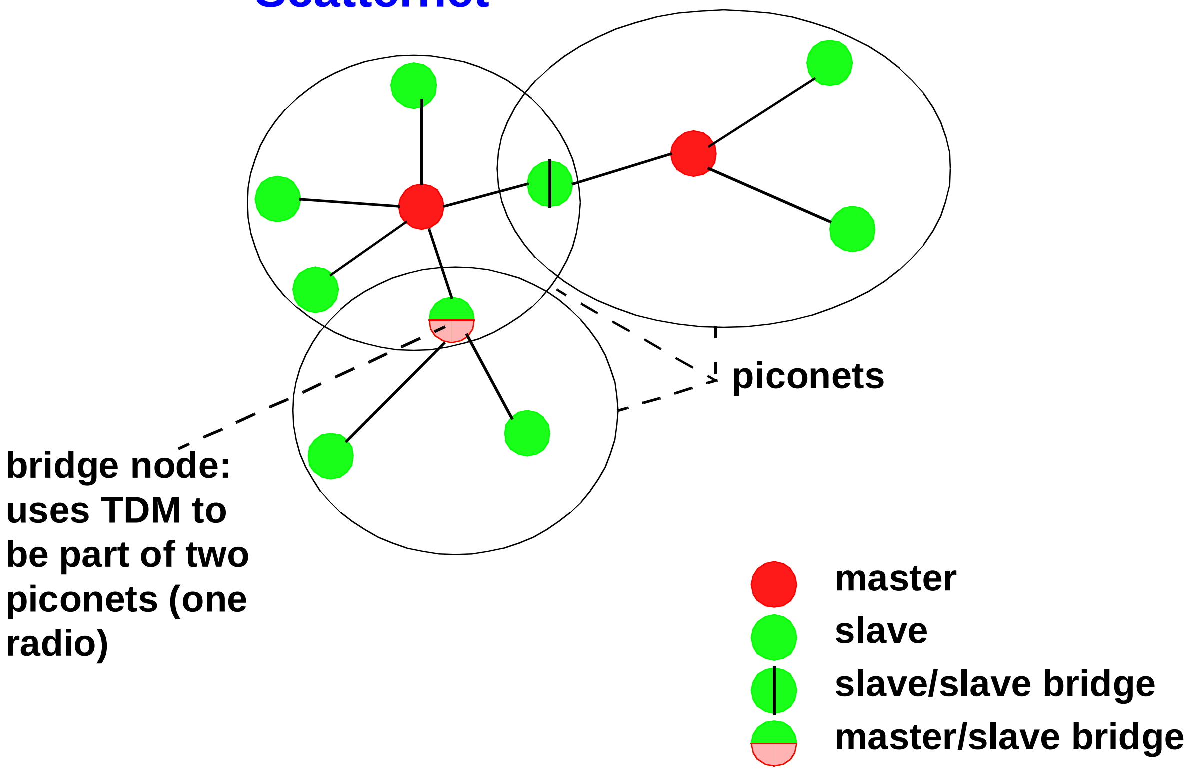
Nodes may act as master, slave or as a bridge between piconets

Typical topologies: ad-hoc

Piconet



Scatternet



Technology Comparison

	Range	Frequency bands	Channels	Capacity
WLAN 802.11	30 - 300 m	2.4 & 5 GHz	14 (3 orthogonal)	2 - 54 (600) Mbps
WMAN 802.16	1 - 50 km	2 - 66 GHz	~10 - 17 (orthogonal)	32 - 134 Mbps
WPAN 802.15	1 - 100 m	2.4 GHz	79	1 - 3 (480) Mbps

Mapping technologies to application scenarios:

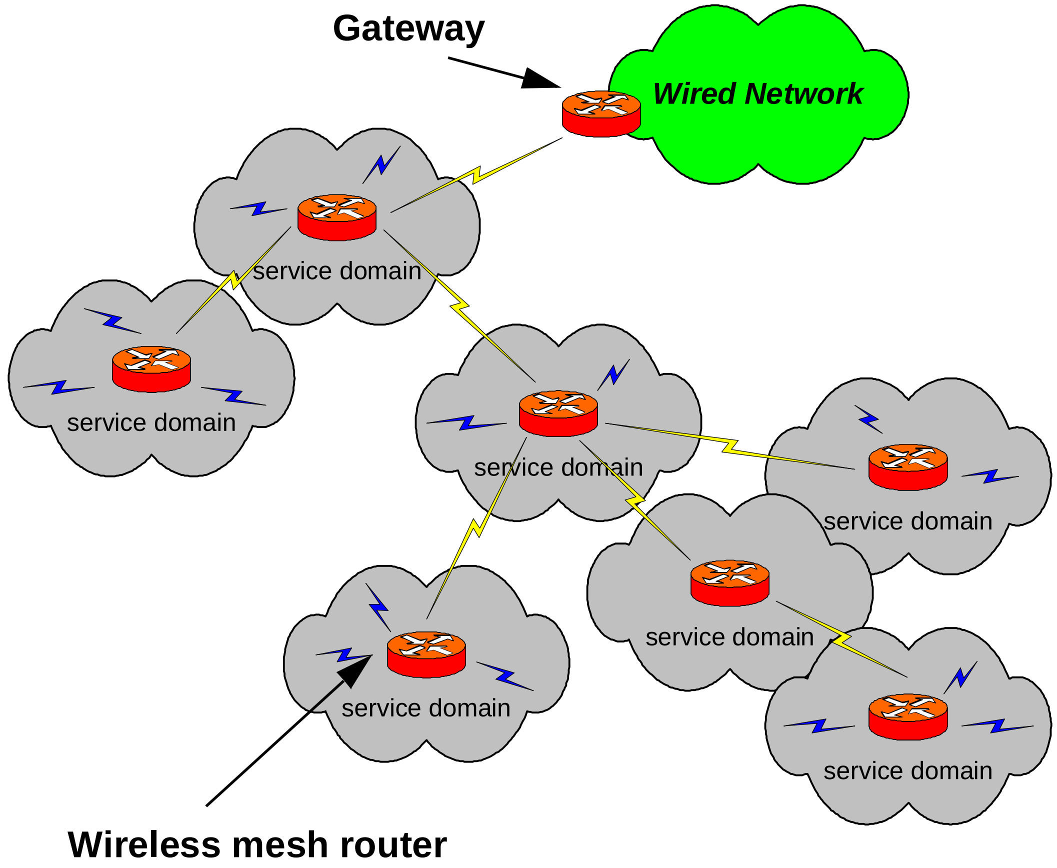
Application Scenario	Technology
last mile	WMAN (WLAN)
community mesh network	WLAN, (WMAN)
City-wide wireless coverage (blanket)	WLAN, (WMAN)
spontaneous mesh network	WLAN, WMAN, WPAN
industry breakdown	WLAN, (WMAN)

Note: Mesh idea is not tied to a particular wireless technology!

Case Study: TOWN Project

TOWN = Telephony Over Wireless Metropolitan Area Networks

Application scenario



Disaster recovery/public safety:

- ~40 wireless mesh routers
- Forward traffic from other routers
- Connectivity for telephony (e.g. GSM base station)
- ~1-4 gateways to fixed infrastructure
- Traffic demand fixed and known

TOWN Project: Requirements

Call-route discovery in dynamically constructed multi-radio WiMAX mesh networks

Stepwise refinement of system (project phases):

(1) Construct static mesh network to handle data traffic (abstract from telephony)

(2) Refine construction to handle joins & leaves of nodes (introduce dynamics into topology)

(3) Invent distributed telephone call-routing (overlay on data network)

(4) Implement a demonstrator system suitable for field tests (proof of concept)

Focus of this lecture: construction of an optimal static mesh network (phase 1)

Constraints

Traffic pattern is known and fixed (2 Mbps downlink, 2 Mbps uplink per mesh router)

- downlink means traffic from gateway to mesh router (uplink vice versa)

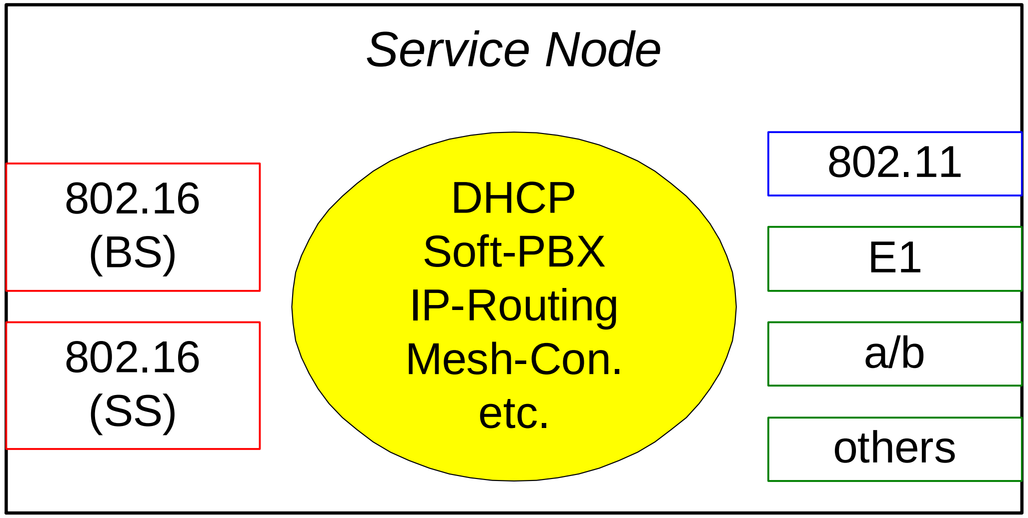
Operate GSM base stations connected to mesh routers
(meet Metro Ethernet‘s QoS requirements)

- Delay < 25 ms
- Jitter < 10 ms
- Frame loss < 8.75×10^{-7}

Consider extensibility right from the beginning on

TOWN Project: Basic Node Structure

Identically equipped mesh routers (= service nodes):



2 WiMAX radio interfaces

3, 10 or 12 orthogonal channels

Interfaces for:

- GSM base station (E1)
- WLAN (802.11)
- Analog telephony (a/b
- Wired Ethernet (among others)

TOWN Project: Problem Statement

Main task is the *dynamic mesh construction*

Initial situation after node deployment

Node positions are given, but unknown (no coordinates, no distances)

Each node may detect other nodes inside of his communication range

- Detection includes a SNR measurement to evaluate link quality

Radio channel may be selected individually for each radio interface

Gateway nodes are marked a such (known)

Problems to be solved

Assign each node to a „cell“ (set of 1 base station and n subscriber stations)

Interconnect cells (use second radio interface to build a bridge, if required)

Assign channels to cells in such a way that interference is minimized

Research questions:

- *How to find an optimal topology considering constraints and requirements?*
- *How to minimize interference?*

  NOTE: these two questions are interdependent!

TOWN Project: Methodology

Reduce complexity by problem decomposition („divide-and-conquer“):

(1) Topology Construction (TC)

(2) Channel Assignment (CA)

Iterate steps (1) and (2) until a viable solution is found

Topology construction means selection of links and grouping of nodes

- Node positions and possible communication links are know in advance
- Some links should not be used (due to redundancy, topology constraints, poor link quality)
- As a result the „cell structure“ of the network is known (edges selected, BS/SS roles assigned)

Optional IEEE 802.16 mesh mode is not considered so far

- Mesh mode would allow direct links between subscriber stations

Channel assigment means allocation of a channel to a „cell“ (set of 1 BS and n SS)

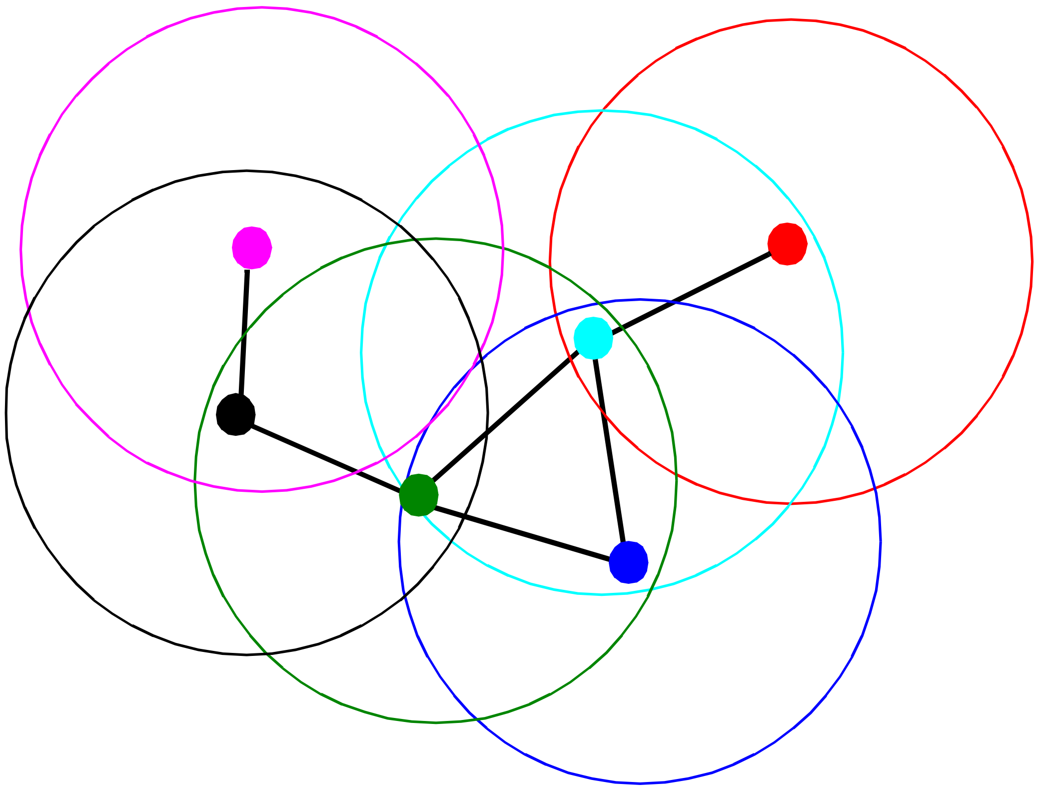
- Use a new channel for each cell to minimize interference
- If all channels are allocated then „re-use“ some channels in an „intelligent“ way

Configurable channels (3, 10 or 16) are orthogonal:

- Given by IEEE 802.16 standard/technology definitions
- Orthogonality means in this context that neighboring channels do not interfere
- The case of only 3 channels would allow us to use the topology constrcution for WLAN, too

TOWN Project: Topology Construction (TC)

Set up a **weighted connectivity graph** (weight = edge label = link quality metric)
Use a well chosen strategy to determine a subgraph as “start-off topology”



For simulation:
- Use „random“ node placements
- „Draw“ circles to indicate communication ranges
- Nodes inside of circle are neighbors
- Calculate SNR for each link and use as link label

In reality:
- Each node detects his neighbors by using a scan-mode
- Detection includes link quality measurement (e.g. SNR)
- Store and replicate information

TOWN Project: Topology Construction (TC)

Search for Solution (considerations)

Topology has to be built from „cells“ (1 BS/ n SS)

- Minimize number of cells since channels are a scarce resource
- A full mesh would imply a big number of cells (drop less important links)

Delay is critical

- Preliminary simulations indicate a value of approx. 5 ms per link
- Minimize number of hops from each node to gateway
- Keep number of hops between any node pair small

Link quality is important (we are going wireless..)

- Avoid poor links even if on shortest path
- Assume that weight reflects minimal link quality (if link quality is varying over time)

Evaluate potentials of different bridge structures (BS/BS, BS/SS, SS/SS)

Consider heuristics if problem is NP-complete

Evaluate solutions by simulations

Don‘t forget extensibility (e.g. joins and leaves of nodes)

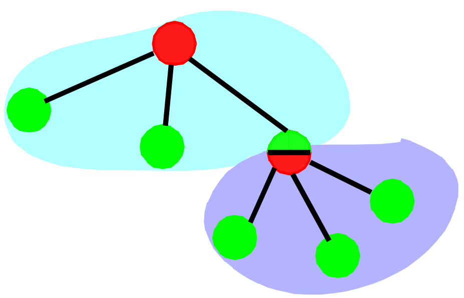
TOWN Project: Topology Construction (TC)

Basic Building Blocks of Topology

Mesh routers with two interfaces can be assigned different roles

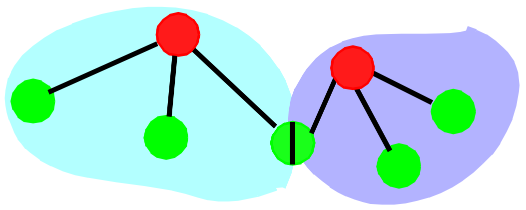
- Gateway
- Leaf node
- Bridge (3 different forms)

SS/BS Bridge



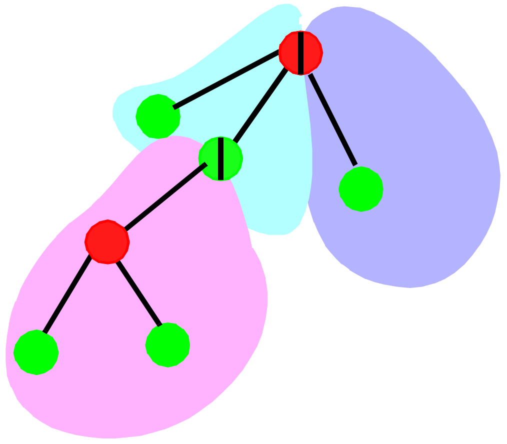
Max. two hops

SS/SS Bridge



Max. three hops

BS/BS Bridge

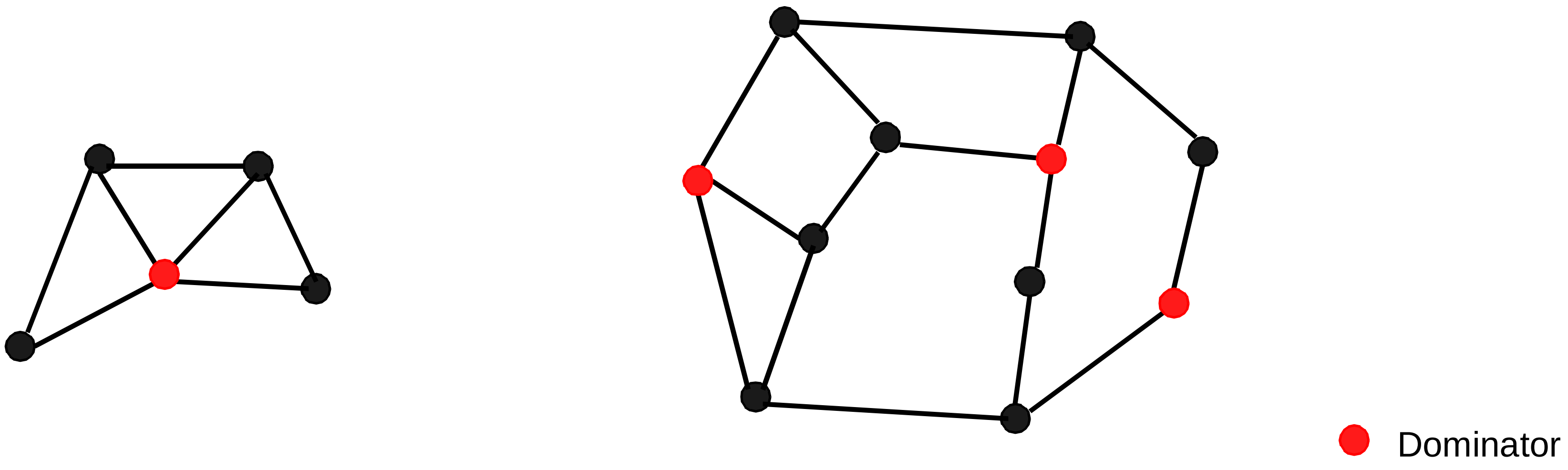


Max. three hops

TOWN Project: Connected Dominated Set

Dominating set of a graph:

- Dominator vertices = Members of the set
- Dominated vertices =Vertices that are adjacent to one or more dominator vertices
- Property: A graph can have numerous different dominating sets of varying sizes

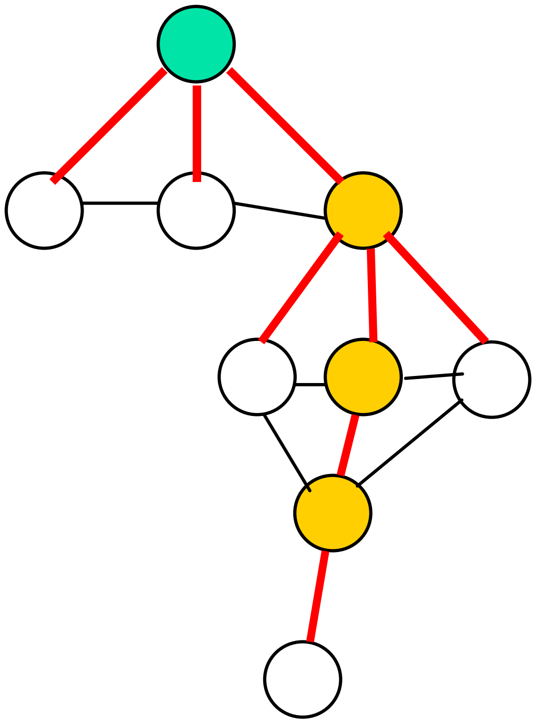


Connected dominating set consists of:

- Dominating set itself
- Additional vertices to interconnect the dominating vertices

TOWN Project: Topology Construction (TC)

Situation for 1 Gateway



Given

Weighted connectivity graph

Weights represent link qualities

One gateway

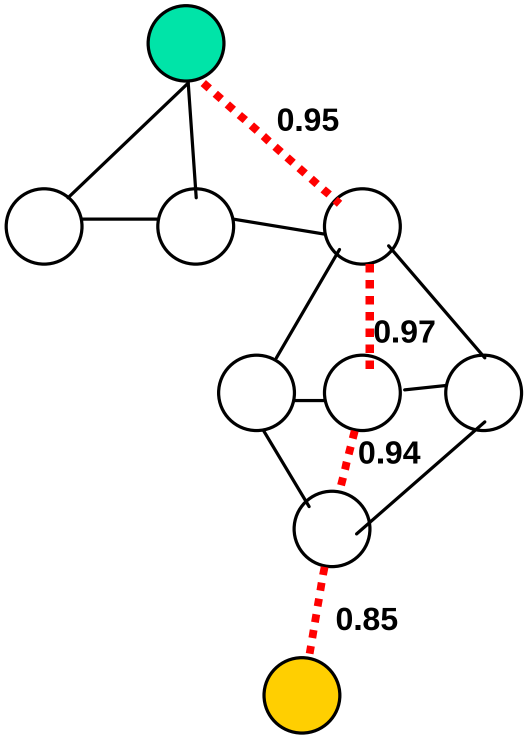
Wanted

Connected dominating set (“base station on nodes”)

Link selection that maximizes the “quality” of the path from each node to the gateway

TOWN Project: Topology Construction (TC)

Deducing Path Quality



p(path)=0.95*0.97*0.94*0.85=0.74

Deduce path quality from link qualities

Link qualities:

- Continuous between 0 and 1
- 0: very bad; 1: excellent – must use, if possible

Estimate of path quality (node <-> gateway):

$$p(path) = \prod p_i(link))$$

Intuition:

- Link quality = probability of correct bit delivery
- Path quality = product of link qualities on path

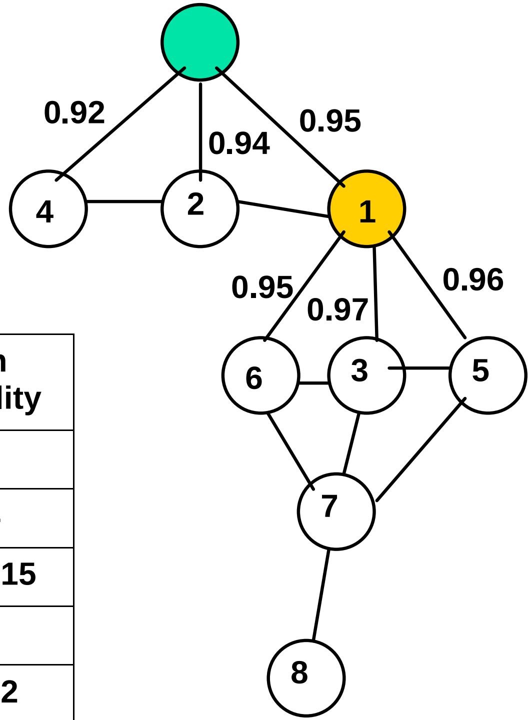
(if we assume independence of link probabilities)

Property:

- Continuous between 0 and 1
- 0: very bad, 1: excellent
- Path quality monotonously decreases from gateway through the network

TOWN Project: Topology Construction (TC)

Dijkstra‘s Algorithm



	Path quality
1	0.95
2	0.94
3	0.9215
4	0.92
5	0.912
6	0.9025
..	..

Wave front algorithm

- Start at gateway
- Consider nodes adjacent to the wave front
- Choose the node with the highest path quality
- Assign the next number to this node
- Store the path quality up to that node
- Mark the edge that connects the node
- Put the parent node into the backbone set
- Advance the wave front to connect the next node ...

TOWN Project: Topology Construction (TC)

Properties of Algorithm

Produced backbone set is connected dominating set

- Only nodes in this set need to turn on BS interface

Path qualities are maximized

- No better way to connect nodes

Low complexity

- Graph traversal
- Essentially node enumeration
- Using a simple algorithm results in $O(|V|^2)$ with V as set of vertices
- In case of sparse connectivity graph $O(|V|*\log(|V|))$ is achievable

Fast convergence

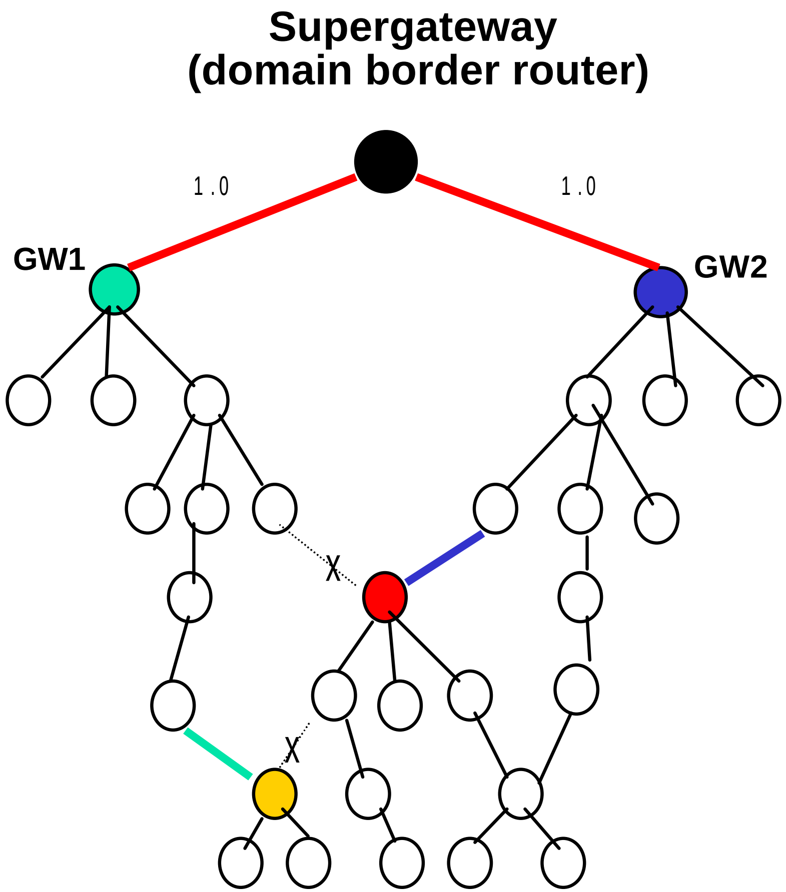
- Fast convergence for initial topology construction (use flooding)
- Convergence delay during operation depends on update strategy (not yet defined)

Overall quality of resulting topology expected to be good for most cases

- Number of hops taken into account by multiplying the link qualities
- Special situations might lead to paths containing many hops (potential delay problem)

TOWN Project: Topology Construction (TC)

Situation for multiple Gateways



Do performance optimization if node could be connected to either gateway

Add a virtual supergateway that is connected to all gateways (metric=1)

Use Dijkstra algorithm to compute backbone set and maximize path qualities

Red: bifurcation node 1
Yellow: bifurcation node 2
GW1, GW2: Gateway 1, 2

TOWN Project: Topology Construction (TC)

Adding Load Balancing

Extend Dijkstra‘s wave front algorithm

Upon moving the wave front:

- Store to which gateway a new node is connected
- Track the number of nodes connected to each gateway

Employ a composite metric for connection decisions:

$$metric = w \cdot lqm + (1 - w) \cdot lbm$$

lqm: link quality metric

lbm: load balancing metric

w: weight (0 <= w <= 1)

Load balancing metric *lbm*: ability of gateway to accept new nodes

$$lbm = \frac{GWcapacity - numAlreadyAssignedNodes}{GWcapacity}$$

TOWN Project: Topology Construction (TC)

Connection Decision

Example for a connection decision at a particular bifurcation node

	lqm	**lbm**	**metric (w=0.8)**
GW1	0.90	0.50	0.82
GW2	0.95	0.20	0.80

w = 1 (only consider path qualities)

- Connect to GW2

w = 0 (only consider load balancing)

- Connect to GW1

w= 0.8 (perform a trade-off)

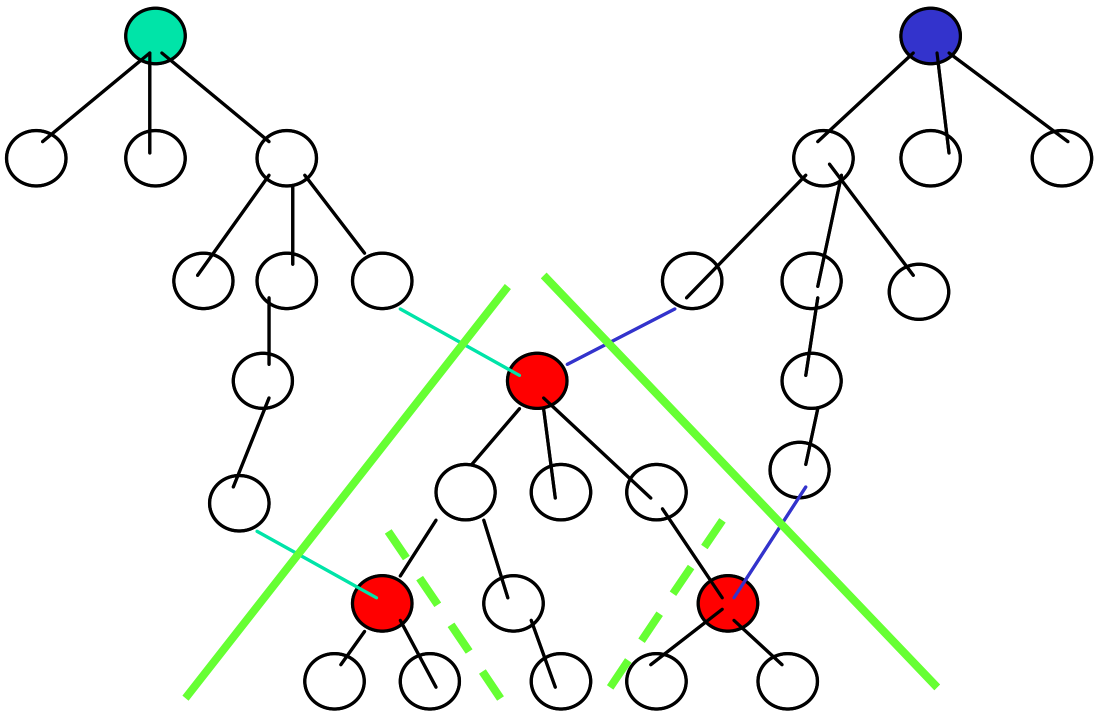
- Connect to GW2

TOWN Project: Topology Construction (TC)

Alternative Approach for Load Balancing

Use clustering to define a „look-ahead lbm“:

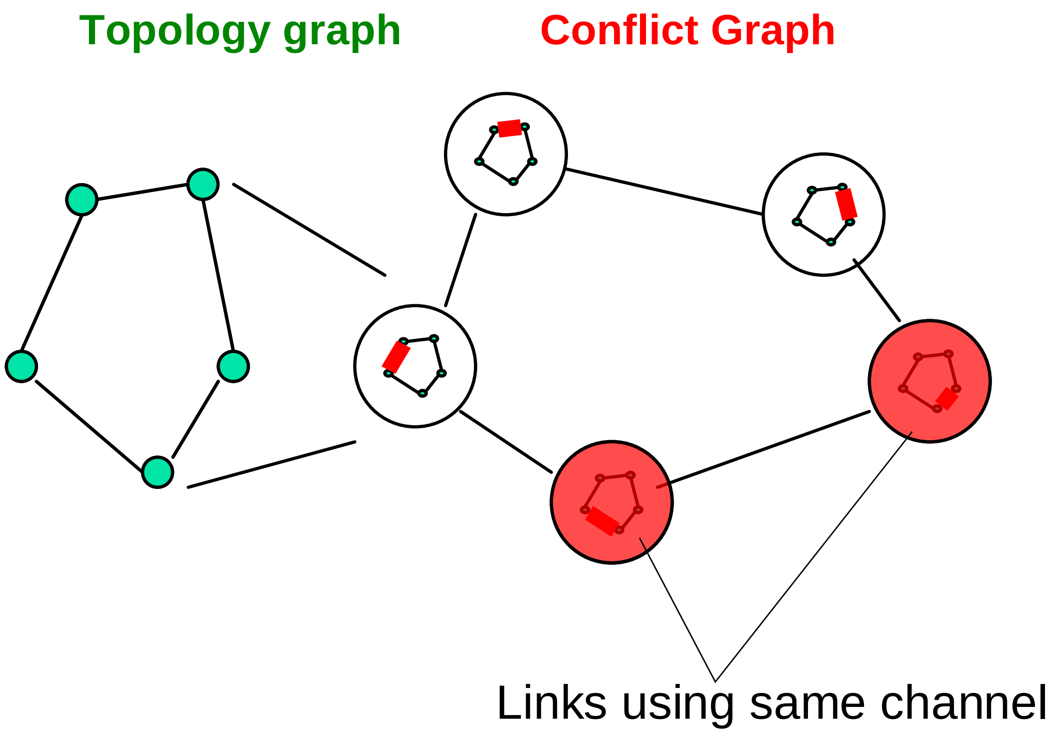
- Take into account the number of new nodes to be connected



TOWN Project: Channel Allocation (CA)

"Standard" graph theoretical approach [Gupta, 2006]

- Set up a conflict graph that models potential interference relations
- Minimize potential interference by computing **max-k-cut** to this graph



Conflict graph:

Vertices = links

Edges = interferences

Interference elimination:

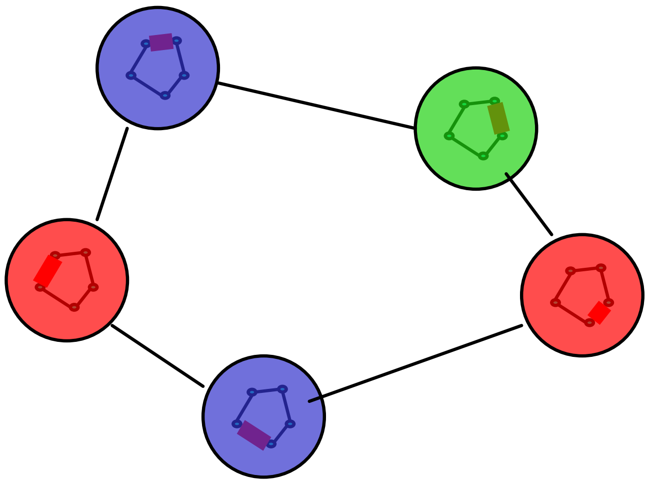
Assign different channels to interfering links

Number of available channels is limited

TOWN Project: Channel Allocation (CA)

Optimizing Channel Allocation

Conflict Graph



Graph coloring:

Channel allocation = coloring nodes

Objective for graph coloring:

Maximize number of edges that connect nodes with different color

Equivalent to maximizing number of links that do not interfere

Problem is known as the *max-k-cut problem*

k = #colors = #channels

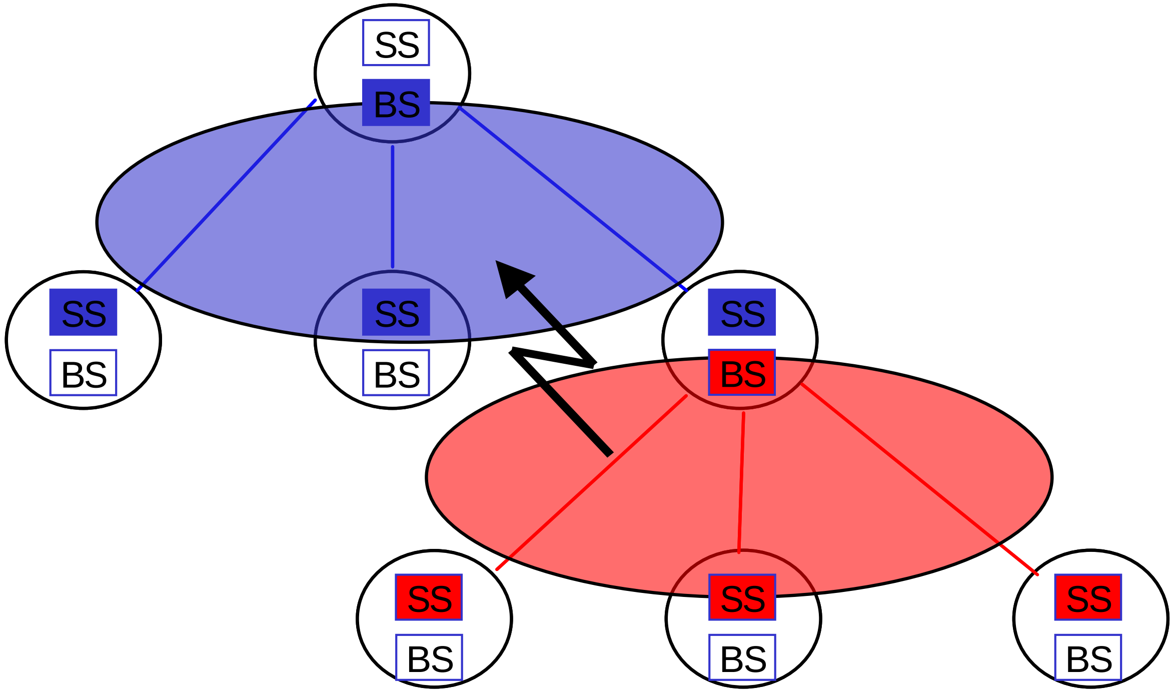
TOWN Project: Channel Allocation (CA)

Applying Graph Coloring to TOWN Topology

Standard approach is based on link level interference (contention based MAC)

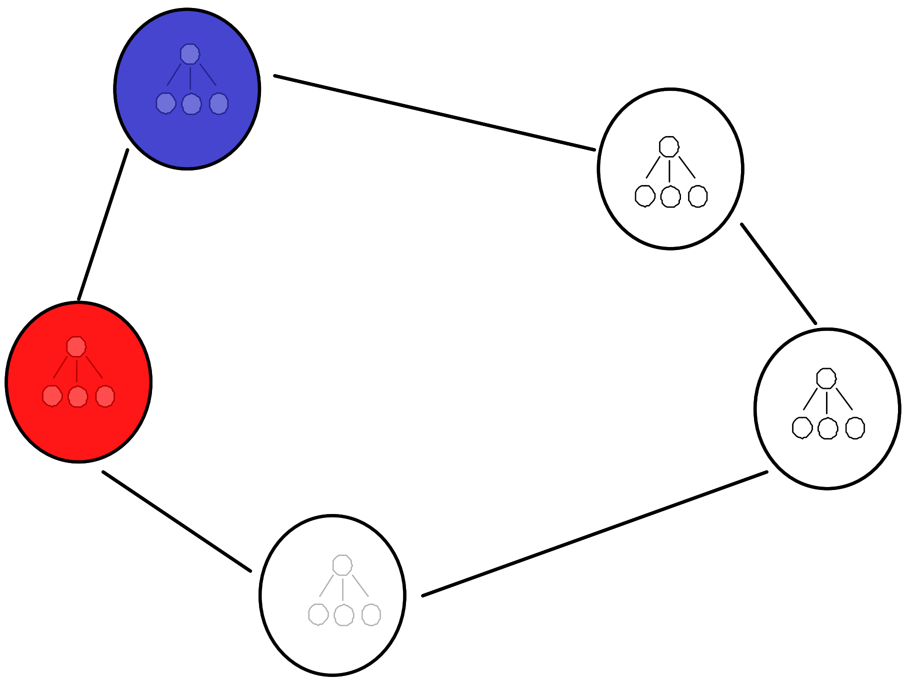
But WiMAX uses TDMA (scheduled MAC): cells do interfere, not individual links

WiMAX cell = set of links associated with a base station interface



TOWN Project: Channel Allocation (CA)

Conflict Graph for TOWN Topology



Nodes represent cells

Calculate max-k-cut to minimize interference

Max-k-cut is NP-complete:
- Focus on general case (arbitrary node count)
- Use heuristics

TOWN Project: Channel Allocation (CA)

How to determine the Conflict Graph

Not an easy task since interference depends on traffic pattern

Deduce conflict graph from connectivity graph and topology graph

Refine graph by tests if required

- This question needs more work

Test all links using broadcasts from on one or more nodes

- Broadcast Interference Ratio (BIR), approximates link interference ratio (LIR)
- Needs $O(n^2)$ experiments to estimate $O(n^4)$ link interference ratios

TOWN Project: Channel Allocation (CA)

Calculation of max-k-cut

Max-k-cut is known to be NP-hard

Use algorithms that approximate the optimal solution (some candidates shown below)

Greedy allocation:

- Go to each node in the conflict graph and compute the locally optimal solution

Merge allocation:

- Start with a distinct (virtual) channel for each node/base station
- Continuously merge two channels to one until the number of channels used equals the number of available channels

Genetic allocation:

- Take an allocation as DNA
- Fitness function that evaluates interference

Tabu-search of an allocation

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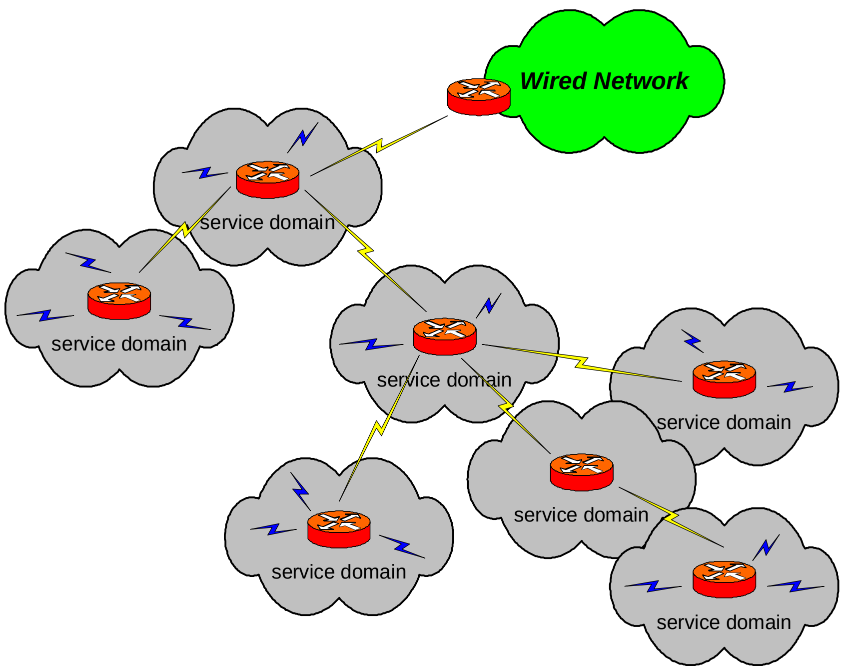
TOWN Project: Channel Allocation (CA)

Greedy Allocation



Assign channels to base stations starting from gateway

At each node: scan all channels; assign the channel with best SINR

Variants
- Breadth first
- Most interfered first
- Weighted with traffic load

TOWN Project: Channel Allocation (CA)

Combining TC and CA: Iteration Algorithm

Compute channel allocation for „start-off topology“

- If this allocation is interference-free, we are done

Else try to modify the topology in a way that could repair interference problems

Iterate this process until an interference free solution is found

- If this solution cannot be found, use the best topology/channel allocation with regards to QoS degradation

TOWN Project: Mesh Construction

TC/CA Evaluation by Simulation

Simulation tool: QualNet 4.0

- Advanced wireless model implements MAC and PHY layer of IEEE 802.16

Scenarios:

- Random node placement
- Grid node placement
- Realistic scenarios defined by industry partner

Traffic pattern:

- CBR (Constant Bit Rate) over UDP
- 2 Mbps uplink and downlink flows between each mesh router and gateway

TC algorithms to evaluate:

- Shortest path (minimize hop count)
- Weighted Dijkstra‘s algorithm (link quality metric, load balancing)

CA algorithms to evaluate:

- Random channel allocation
- Variants of greedy algorithms

TOWN Project: Mesh Construction

TC/CA Evaluation by Simulation

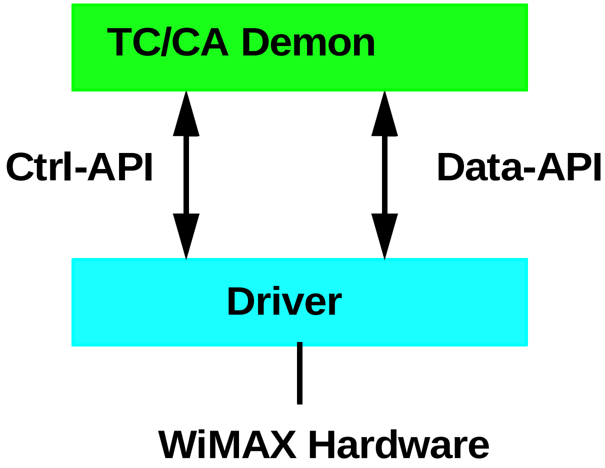
Evaluation metrics:

- Constraints (delay, jitter)
- Packet delivery rate, packet error rate
- Fairness
- Aggregate throughput
- Extensibility

Credible simulations:

- Do our evaluation metrics model the relevant properties in relevant scenarios?

Mesh Router Software Architecture

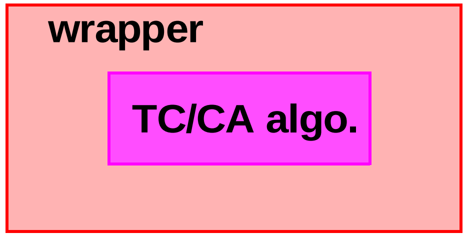


Ctrl-API: IOCTL's for
- Queries of {SNR, ID} for all nodes in comm. range
- Assigment of channel freq.
- Setting transmit power*

Data-API: similar to Ethernet-API

*: only for base stations; for TOWN: all BS use same transmit power level

TC/CA demon internals:



wrapper: acts as an adapter for TC/CA algorithms; abstracts from actual Ctrl-API.

Each mesh router uses a linux based operating system

WiMAX hardware for demonstrator is a COTS (Common-Of-The-Shelf) product

Goal: Use WiMAX NIC driver „as-is“

Summary

Mesh networks may be based on IEEE 802.11, 802.16 or 802.15 technology (among others). Basically the mesh idea is not tied to a particular wireless technology.

Implementing a well performing wireless mesh network requires a sufficient connectivity (node degree > 2), a well chosen topology (link selection) and effective interference avoidance.

Using graph theory enables us to model niceley the connectivity and interference relationships of a wireless mesh network.

In a real-world wireless network, the connectivity graph and the interference conflict graph may be determined by using SNR measurements.

Summary (2)

A simple algorithm for topology construction uses a shortest path metric. However a more sophisticated variant that considers link quality and load balancing might be more suitable.

Channel allocation is equivalent to solving the max-k-cut graph problem on the interference conflict graph. Greedy assignments are known to be approximation algorithms for the max-k-cut.

Evaluating simulations of wireless mesh network may involve the delay metrics, packet delivery ratio and fairness among others.

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