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Mesh Network Topology Construction and Channel Frequency Allocation in the TOWN Project

TIK-Report 255

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Executive Summary

The TOWN project addresses employing mesh routers with multiple IEEE 802.16-2004 interfaces to construct self-organized backhaul telephony networks for public safety scenarios. Given this context, this report reviews TOWN specific requirements, and proposes to decompose the self-organized network construction problem to a topology construction problem and a channel allocation problem. This decomposition allows us to draw a relation from the channel allocation problem to the well known max-k-cut problem in graph theory. A key property of the max-k-cut problem is that this problem is known to be NP-hard. This means that it is not feasible to compute the optimal channel allocation at non-trivial scenario sizes. However, even after discussion with widely-recognized communication theory experts such as Roger Wattenhofer from ETH Zurich and Stefan Nilsson from KTH Stockholm, we do not see any simpler modeling of the problem that this decomposition.

This report thus reviews related work and proposes a pragmatic approach that is based on combining heuristic algorithms/schemes that approximate the optimal solutions for the topology construction and channel allocation problem. This approach of iterating topology construction and channel allocation until a reasonable solution is found has the potential to achieve viable results for self-organized mesh network construction. However, another consequence of this modeling is that it may not be possible to determine how much space for optimization will be left although we can and certainly will evaluate the performance of the proposed algorithms/schemes.

Thus, optimizing and tuning the heuristic algorithms will be an important issue in the future. We expect that with more precise information about the application scenarios considered by ASCOM, the optimization focus can be made smaller and the algorithms can be improved towards better performance.

1. Introduction

Wireless mesh networks [60] are multihop networks of **wireless routers**. There is an increasing interest in employing wireless mesh networks as distribution networks to provide network connectivity in disaster recovery and **public safety scenarios** where voice communication is key.

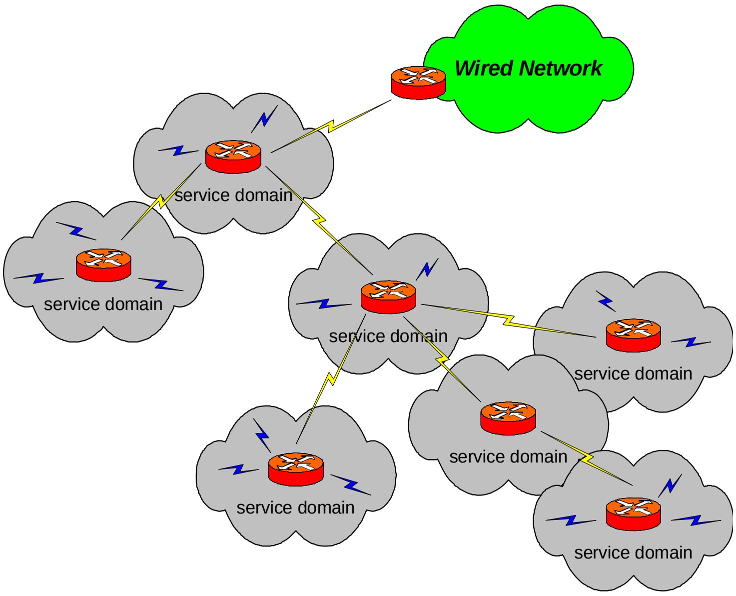


Figure 1: Wireless mesh network

Given this context, TIK/ETHZ and Ascom started the **TOWN project** (telephony over wireless metropolitan area networks). The goal of the project is to lay the technological foundations for Ascom to build, deploy and operate wireless routers that build on off-the-shelf IEEE 802.16-2004 technology.

An important design goal for these wireless mesh networks is **capacity** which is well-known to be severely limited by **interference** of wireless network links in multihop settings [61]. The standard approach to alleviate this capacity problem is to employ **multiple channels** [62]. Non-interfering orthogonal channels are employed for conflicting wireless transmissions. The technology used in the project provides 3,10, or 12 channels for conflict resolution.

The research community has started exploring how to best use multiple channels in multihop wireless networks. One line of research has focused on **channel switching** on the same radio interface [65,66,67]. All these research works propose channel switching at a fast time scale (per packet or per handful of packets). Some of the works also propose dedicated MAC protocols or extensions of existing MAC protocols. For the TOWN project such propositions are in conflict with using standard IEEE 802.16-2004 hardware which has channel switching delays that are in the order of several milliseconds.

The approach that TOWN takes is to employ **multiple radio interfaces** on each wireless router and assigning different channel to these interfaces. The line of research that has focused on this approach is essentially documented in [1,3,5,9]. This approach makes it easy for a router to utilize multiple channels without any requirements of fast channel switching and be easily implemented on top of off-the-shelf IEEE 802.16-2004 hardware. The channel assignment here can be static or dynamic. However, dynamic schemes are limited to changes on a long time scale so that overheads such as high channel switching delays are justified.

However, reviewing this literature [1,3,5,9] we have found that research is **focused on very specific scenarios** which is closely tight to very specific mathematical formulations. These mathematical formulations are heuristics to find approximate solutions for some optimization problem which is usually identified to be NP-hard. Most of the papers reviewed do not go beyond showing that the proposed heuristic leads to a channel allocation that works reasonably in their specific scenario. The difference to the optimum allocation (i.e. optimal solution to the NP-hard problem) is not evaluated simply because it is computationally not feasible to find an optimal allocation for scenarios of reasonable size.

This **report is structured** as follows. We start with reviewing the scenario and the technology of the TOWN project. We note that this review certainly requires additional and more concise input from ASCOM, particularly on the application scenario. We then give a problem formulation which decomposes topology construction and channel allocation in a way that a relation between the channel allocation and the NP-hard max-k-cut problem in graph theory can be made. Next we list heuristic-based schemes/algorithms for both topology construction and channel allocation. In a separate section, we discuss how a simulation study could be set up to evaluate the identified schemes before reviewing some implementation issues that come along with the implementation of these schemes/algorithms on the ASCOM demonstrator. Finally, the report concludes with a recommendation how to proceed with the project. The most important point here is that this pragmatic approach of developing heuristic based schemes together with concise information from ASCOM has the potential that business solutions evolve out of the TOWN project.

2. TOWN Specific Requirements

2.1 Requirements coming from the technology

The TOWN project assumes that network nodes ("service nodes") are equipped with **multiple air interfaces** compliant to the IEEE 802.16-2004 standard.

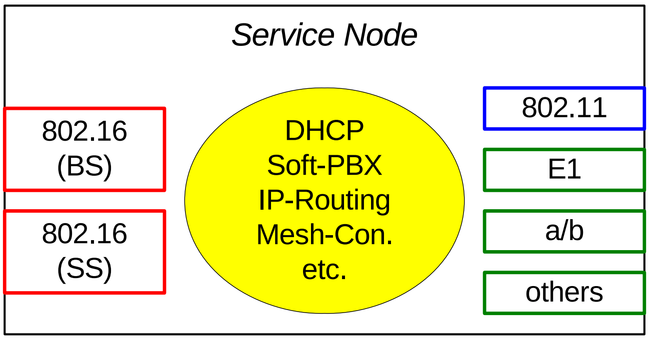


Figure 1: Structure of a Service Node

The standard supports only three modes for interfaces: base station mode, subscriber station mode, and scanning. The standard does not support ad-hoc mode. In base station mode, the interface can be tuned to one of the 3,10,12 **orthogonal channels** and then offers network connectivity on multiple other nodes that have an interface in subscriber station mode. This leads to **point-to-multipoint links** that all operate at the same channel. This channel sharing is not assumed in the literature on mesh networks [1,3,5,9]. Moreover, interfaces can scan the orthogonal channels and measure the signal-to-noise ratio. In addition, IDs of base stations that can be heard on the channel can be identified.

To start, we assume that nodes have two interfaces. Then network topologies are restricted to trees.

2.2 Requirements specific to the public safety scenario

The TOWN scenario assumes that the network size is limited to **40 service nodes**. Neither wireless network capacity, nor storage capacity in the nodes, nor power is scarce. Thus, it is reasonable to assume that the nodes in the network exchange and **track all information** on topology, channel allocations, and scanning results of other nodes in the network.

Node joins and leaves are rare. Nodes are usually not switched of or added during operation. When setting up a network, dozens of nodes join at a time.

The **traffic demand** in the network is in the worst case 2 MBits/s from each node to the gateway and and 2MBit/s back. This capacity is enough that a GSM/UMTS base station can be attached to the node. Since the theoretical maximum of the gateway's BS interface is 80 MBit/s (up and down direction together) and link utilization should be kept below 50%, gateways may only serve 10 nodes. Thus, to support 40 service nodes, a minimum of **4 gateways** will be required.

The base station's traffic is telephony which is **sensitive to disruptions**. Thus, the QoS requirement in the wireless mesh network is not only enough capacity to fulfill the traffic demand but also to limit disruptions due to channel switching and packet loss.

3. Review of the Problem Statement

Figure 1 depicts a mesh network. The part of problem statement given in the TOWN proposal that is relevant to this report is to "*find an algorithm for self-organized mesh network construction and channel allocation that minimizes QoS degradation due to interfering links*." However, the TOWN proposal says little on how this statement can be translated into optimization goals or how the problem could be attacked. We thus propose to apply a **divide-and-conquer** strategy to divide the problem up into subproblems. Next we identify relations from the subproblem to problems that have already been studied in other research projects.

Presumably mesh network construction is topology construction, i.e. which links to select to form a network that connects all nodes to the gateway. Channel allocation is thus the allocation of a frequency to a communication links.

Following this strategy we propose to decouple this topology construction from channel allocation (which frequency is used for communication on particular links). This decoupling allows us to relate channel allocation to a graph theory problem. In a further step we may iterate topology construction/channel allocation until we have found a solution that fulfills our requirements.

3.1 Topology construction problem

This subproblem is to construct a loop-free topology that interconnects the immobile service nodes in a way to one of the gateways that can be reached from each node. Finding a scheme that produces an arbitrary solution to this problem may not be difficult. However, finding a scheme that produces a solution that has the potential to minimize interference after channel allocation may not be easy. Thus, it is not clear what objective the scheme is supposed to optimize for. This leads to number of possible problem formulations.

Formulation 1:
A simple formulation for the topology construction problem is as follows. The input may be a directed acyclic graph with the information of which pairs of nodes are within communication range. A possible objective then is to **minimize the overall number of hops** to the gateway for all nodes and to balance the network load/node degree in case of tie in number of hops. We note that this formulation may have more than one optimal solution.

Formulation 2:
An alternative formulation of the problem could account for link qualities by assuming that **all nodes tune their BS interface to a unique specific channel**. At the same time these nodes conduct SNR measurements at their SS interface. The result of these SNR measurements makes up the **link quality matrix**. The optimization goal in this topology construction problem then may be to maximize the overall sum of SNRs on the subset of the links that make up the spanning tree. Frequency allocation may then lead to further optimizations.

Formulation 3:
More complex formulations of the topology construction problem may to account for **link qualities and link interferences**. To do so, all nodes may tune their BS interfaces to the channel that they are actually supposed to work with. This may help to perform iterations between the topology construction and channel frequency allocation until requirements are met. This may also help for **incrementally joining nodes.**

3.2 Channel frequency selection problem

The second obvious subproblem that needs to be attacked is the channel frequency allocation problem. Before coming to problem formulations, we suggest a network and an interference model that allow us to relate the problem to known graph theory problems.

3.2.1 Network model

We consider a wireless mesh network with stationary nodes with multiple IEEE 802.16-2004 compliant interfaces. We then assume that each node's base station interface potentially has a number of communication links to multiple subscriber station interfaces of other nodes. We refer to this number of links with the word ***set***.

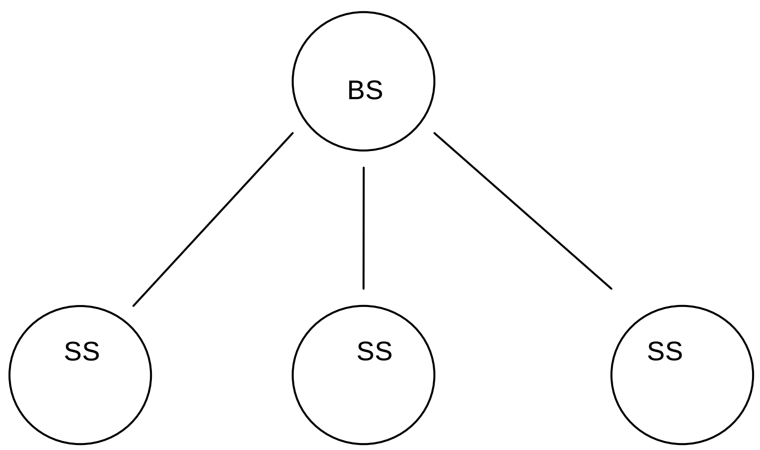


Figure 3: Set of links served by one base station interface

3.2.2 Interference Model

Due to the broadcast nature of the wireless link, transmission along a communication link (between BS and SS) may interfere with transmissions along other communication links in the network. Two interfering links cannot engage in successful transmission at the same time if they transmit on the same channel. A similar argument can be made for a two sets in our network model. Two sets operating at the same channel interfere when any of the links of the 1st set interferes with any of the links of the 2nd set[1].

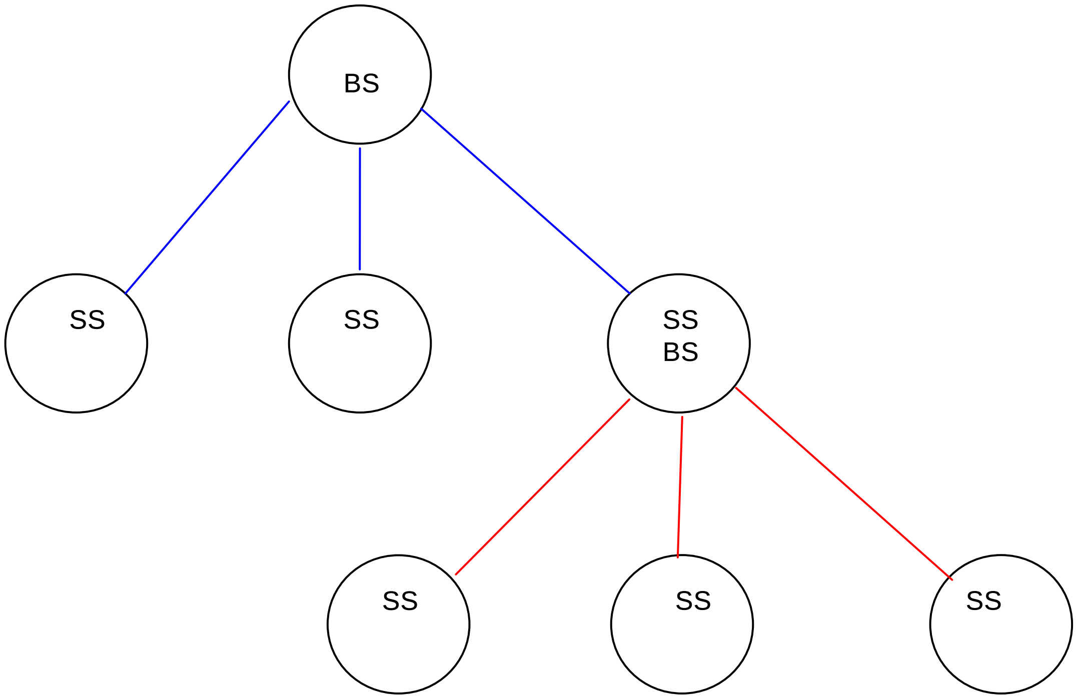


Figure 4: Two sets that interfere when operating on the same channel

Then, for the number of sets in a IEEE 802.16-2004 based wireless mesh network, the *interference model* defines which **pairs of sets** have interference when operating on the same channel and which have not. This definition is independent a specific interference model and can be used both with the physical and the protocol interference model. Interference in this model can both be binary (does interfere of does not interfere) or fractional (give a number between 0 and 1 that represents the degree of interference).

This interference model allows us to define **conflict graphs** for potentially interfering sets. This in turn allows us to attack the problem "in a standard way". We thus propose the following problem formulations.

[1] We note that to detect pairs of interfering sets, all interfaces of the 1st set need to check whether they can hear beacons of any interface of the 2nd set and vice versa.

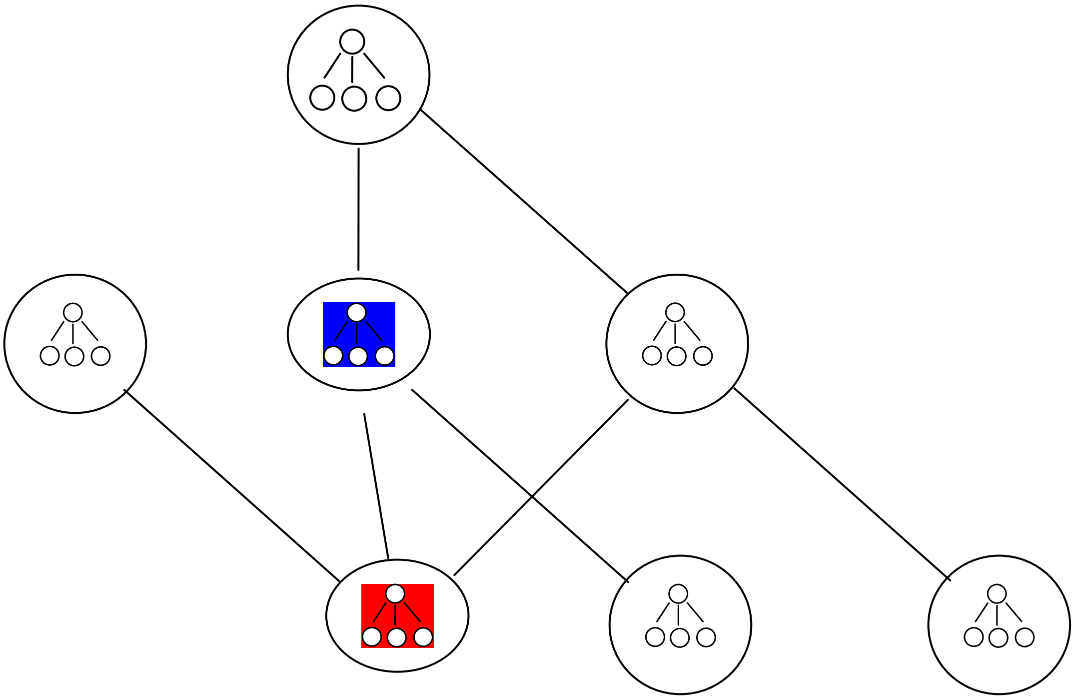


Figure 5: Conflict graph that models interference between sets

Formulation 1:
Set up the conflict graph by defining the sets as nodes and the interferences as edges. Assigning channels to the sets is the equivalent to coloring the nodes in the conflict graph. The number of colors is equivalent to the number of available channels. The optimization problem is then to color the nodes such that the number of edges between nodes of the same color (= remaining interference) is minimized. This is equivalent to maximizing the number of edges between nodes of different colors which is the **well-known k-cut graph theory problem [71]**. This problem is known to be NP-hard. The standard way how this problem is solved is with some heuristics, e.g. with tabu-search and merge or greedy as the optimal solution would require the traversal of an excessive search space (see upcoming paper from Gupta for details).

Formulation 2:
Same as formulation 1; however use weight on edges of the interference graph for the **degree of interference** and the **amount of traffic** that is sent over the set ("fractional interference model"); maximize the summed weight of remaining edges between different vertices that have different colors.

3.3 Interaction between topology construction and channel frequency allocation

Once channel allocation has been performed one might ask whether simple tweaks in the topology construction could avoid major interferences. It may thus make sense to construct a number of topologies and allocate the channels one each of these topologies to check whether there is space for optimization in this **TDMA/frequency allocation trade-off**.

3.4 Extensions of the problems stated / additional problems

- Joins and leaves of nodes
  A joining node may just be "added" as leaf node. This does not require any channel allocation. Later, at a time of low network usage, topology construction and frequency allocation may be reevaluated and adjusted.
- Topology control – adjust signal strength
  no thoughts yet.
- A node has 2 SS instead of 1 SS interfaces -> redundancy
  no thoughts yet.

4. Related work

Up to now, quite some work has been published in the field of mesh networks in general. Most of this work addresses **very specific scenarios** which are closely tight to very specific mathematical formulations. These mathematical formulations are usually heuristics to find approximate solutions for an NP-hard optimization problem. Most of the papers reviewed do not go beyond showing that the proposed heuristic leads to a channel allocation that works reasonably in the specific scenario. The difference to the optimum allocation is not evaluated or estimated simply because this is not feasible with simple means.

We go step by step and present what we have found.

4.1 Topology construction

Formulation 1 of the topology construction has **Raniwala et al. [3]** as related work. [3] proposes topology discovery plus a load aware metric to construct a **fat spanning tree** with more load on links close to the gateway. The reasoning behind this approach is to minimize the load on wireless links where QoS can be degraded. For our application Raniwala's load aware metric is equivalent to hop count with node degree since our traffic demand matrix is constant over time. For more detail on the **topology discovery** used by Raniwala see [30][31].

Formulation 2 has the **Rooftop** project and its papers as related work (see e.g. [35] for the most recent paper that discusses the significance of link quality metrics).

Formulation 3 can employ **greedy algorithms** from graph theory (see [21] for details on such algorithms).

4.2 Channel frequency allocation

Formulation 1 of this problem has a lot of related work in graph coloring (see [20-27]) and linear programming to retrieve performance bounds (see [28](extremely hard to read)). However, it is proven that the problem is **NP-hard [5]**. Thus, we are likely forced to focus the design of channel allocation schemes on **heuristics** such as **greedy coloring** [71] or **tabu-search** [70] with merging.

Adya et al. [9] propose a channel assignment scheme for community networks. [9] does not consider the number of available interfaces in a service node. The channel to use for communication is determined via a measurement-based approach. In [1,3], Raniwala and Chiueh propose centralized and distributed load-aware channel assignment and routing algorithms. In [3], the authors propose a channel assignment scheme for an ISP last mile's wireless network. This greedy scheme can easily handle joins and leaves of network nodes. They assume a tree-based communication pattern to ease coordination for optimizing channel assignment which we also do. However, they do not quantify the performance of their solutions with respect to the optimal. In [10], a purely measurement-based approach is taken for multi-radio channel assignment. Here, one interface is always tuned to a common channel so that the topology is always preserved. This can be wasteful especially in case only a few interfaces are available. Marina and Das [5] address the channel assignment to communication links in a network with multiple radios per node. They propose a centralized heuristic (greedy) for minimizing the network interference. In [8], Das et al. present a couple of optimization models for the static channel assignment problem in a multi-radio mesh network. However, they do not present any practical (polynomial time) algorithm.

Loosely related work on frequency assignment in cellular networks based on graph algorithms can be found on http://fap.zib.de .
Loosely related work in heuristic channel allocation is [1][2][4-8].

Important **recent related work** may be added once the author of this report has visited SIGCOMM CHANTS 2006 (Sept. 2006) and MobiCom 2006 (Sept. 2006).

5. Potential Algorithms

5.1 Topology construction

- Minimize hop count, In case of tie balance load.
- When successively iterating topology construction/channel allocation degraded quality due to interference on specific links should be taken into account.

5.2 Channel allocation

Greedy, Tabu/Merge, Genetic approximation algorithms.

- Greedy: easy to distribute good potential results. For a detailed description refer to [51][71].
- Tabu/Merge: easy to implement, good potential results. For a detailed description refer to [51][70].
- Genetic: presumably close to optimal in a simulation. Good basis of comparison. For a detailed description refer to [51].

To estimate the performance gap from allocations with these approximation algorithms to the optimal allocation, we need to find linear programming since the search space is to large to test all possible allocations. Finding such a linear programming is known to be a hard theoretical problem.

6. Simulation Study

6.1 Simulation Environment.

We have evaluated three simulation platforms to study the combined mesh network construction and channel allocation problem. These platforms are ns-2, Opnet, and QualNet/GlomoSim.

Having great experience with **ns-2**, we found that ns-2 is too heavy-weight for the TOWN project.

Another option would be **OpNet**, with which TIK/ETHZ also has some experience and ASCOM has large experience. However, TIK's experience with the OpNet product support was mixed. With regards to license cost, we found that costs largely depend on whether OpNet agrees to issue an academic license for the TOWN project. Moreover, license costs for OpNet cannot be shared with other projects.

So far, we consider **QualNet** to be the most applicable candidate for conducting the simulations within the TOWN project since

(i) Qualnet offers a layered and well structured implementation and
(ii) TIK/ETHZ has made good experience with QualNet's predecessor Glomosim.

Although it's not a major issue, we note that QualNet is the only simulator with built-in support for the WiMAX MAC layer. Simple functionality for the PHY layer based on BER/SNR curves could be added by modifying the abstract PHY.
With regards to license cost, we found that the cost for an annual academic institute license for QualNet is 3000 Euro. This cost can be shared with other TIK/ETH projects.

Mid of July 2006 Ascom und TIK/ETHZ agreed to use QualNet in the TOWN project. The QualNet license is paid. A full version of QualNet will be available by 10. Aug. 2006.

6.2 Simulation Scenarios (Input from ASCOM required)

The scenarios for which the joint topology construction and channel allocation problem is to be solved are essentially characterized by

- Number of nodes in the WMN.
- Density of nodes (number of nodes in communication range, interference range).
- Spatial distribution of nodes/node placement.
- Channel characteristics (which nodes can potentially communicate/infer with which other node).
- Traffic demand matrix.
- The dynamics of nodes joining and/or leaving.

6.3 Traffic model (Input from ASCOM welcome)

- P2P
- P2GW

6.4 Modeling of interference (Input from ASCOM welcome)

Free space model
2-way ground model

6.5 Parameters space of the simulation (Input from ASCOM welcome)

- The different algorithms and their variants.
- Node densities (distribution of node degrees).
- Node distributions and placements.
- Channel characteristics.
- -> it will be required to somehow reduce the complexity of simulation study.

6.6 Possible evaluation Criteria (Input from ASCOM welcome)

- Performance specific metrics:
    - Capacity for CBR traffic from all routers (“service nodes”) to the gateway.

7. Implementation issues

Early definition of software interfaces of the demonstrator will considerably foster efficient development of the demonstrator.
We thus state the following assumption on the structure of the demonstrator before we specify programming interfaces. The demonstrator consists of the following units.

- Interfaces: 1 BS and 2 SS
- Interface controller: Controls the interfaces, implements the lower protocol stack, offers generic interfaces for both: operation and management unit, forwards received information to the appropriate unit
- Operations unit: Traffic management
- Management unit: Control of interface controller, channel allocation, operation mode

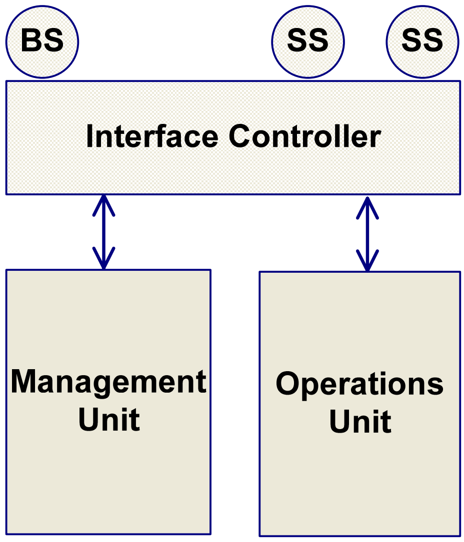


Figure 5: Architecture of Demonstrator

7.1 Management unit

TIK/ETH is responsible to develop the management unit. The Implementation will be done in C or C++. We thus identify the following programming interfaces to the interface's management unit. Detailed interface definitions will be written till end of December.

- External Control Signal / Event
  - Start (for starting and resetting the unit)
  - Management data received (automatically announced by the interface controller)
  - New node subscribed to BS (automatically announced by the interface controller)

- Output
  - set frequency (for active communication)
  - set mode (BS, SS, scan, sniff, off)
    - scan (finding out which channels are used by which neighbors)
    - sniff (passive listening on a freq).

    - send management data

- Input
    - Scanning results (SNR, beacons for each frequency)
    - Sniffing results (SNR, beacons, data)
    - Receive management data

8. Conclusion and Recommendation

In this report, we have proposed a **problem formulation** for the joint topology construction and channel allocation problem in the TOWN project. This formulation particularly accounts for the fact that the technology employed in the TOWN project is based on mesh routers ("service nodes") with multiple IEEE 802.16-2004 interfaces and suggests to decouple topology construction from channel allocation to reduce complexity. Moreover, the problem formulation makes a relation from channel allocation to the max-k-cut problem which is well-known standard problem in graph theory.

Starting from this problem formulation we have reviewed **related work**. We have found that up to now, quite some work has been published in the field of mesh networks in general. Most of this work addresses very specific scenarios which are closely tight to very specific mathematical formulations. These mathematical formulations are usually heuristics to find approximate solutions for an NP-hard optimization problem. Most of the papers have reviewed do not go beyond showing that the proposed heuristic leads to a channel allocation that works reasonably in the specific scenario. The difference to the optimum allocation is not evaluated or estimated. Moreover, we have found that the IEEE 802.16-2004 specific property that all communication is point-to-multipoint communication makes it difficult to draw a relation from TOWN's joint topology construction and channel allocation problem to what is documented in the literature.

To overcome this difficulty, we have proposed to handle a set of point-to-multipoint communication links as one entity. This handling allows us make a relation from TOWN's channel allocation problem to the max-k-cut problem in graph theory which is NP-hard. Thus, it is not feasible to compute the optimal solution for scenarios of reasonable size. Even deriving bounds to the optimal solution is known to be a difficult theoretical problem. As a consequence, **we have proposed** heuristic algorithms/schemes that have the potential to achieve good results when implemented in communication systems. Moreover, we have reviewed simulation platforms and methodology to evaluate these algorithms/schemes. In addition, we have discussed implementation issues that concern the implementation of the demonstrator in the TOWN project (logical structuring of the demonstrator, definition of programming interfaces, etc.).

Based on this vantage point, we recommend putting the focus of the project on elaborating these heuristic schemes. This focus together with concise information from ASCOM on target scenarios has the potential that business solutions evolve out of the TOWN project.

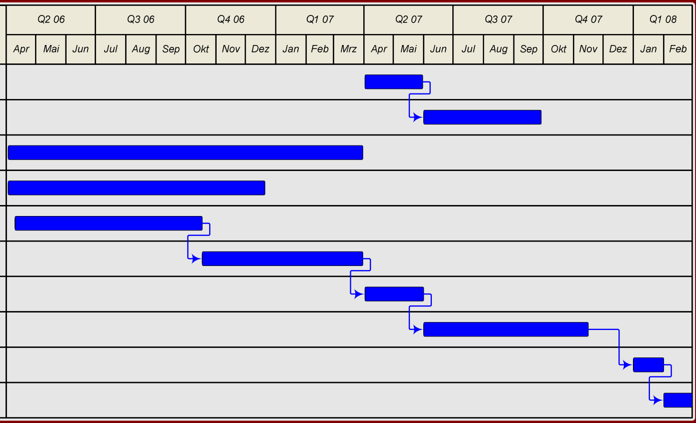
9. Acknowledgement

The author likes to thank Roger Wattenhofer, Gunnar Karlsson, Stefan Nielsson and Rainer Baumann for valuable discussions[2].

[2] Prof. Roger Wattenhofer and Prof. Stefan Nielsson are recognized experts in communication systems theory. Prof. Gunnar Karlsson is a recognized expert in communication systems architectures.

Appendix A: Preliminary Timetable

ID	Task Name	Start	Finish	Duration
1	Theory for terminal location	02.04.2007	30.05.2007	8.6w
2	Simulation for terminal location	01.06.2007	28.09.2007	17.2w
3	Understanding the topology construction/channel allocation probl.	03.04.2006	30.03.2007	52w
4	Study related work topology construction/channel allocation	03.04.2006	20.12.2006	37.6w
5	TC/CA: setting up simulation	10.04.2006	17.10.2006	27.4w
6	TC/CA: simulation study	18.10.2006	30.03.2007	23.6w
7	TC/CA: specification of management protocol	02.04.2007	31.05.2007	8.8w
8	TC/CA: implementation of management protocol in demonstrator	01.06.2007	15.11.2007	24w
9	Field test of demonstrator	01.01.2008	31.01.2008	4.6w
10	Write final report + paper(s)	01.02.2008	06.03.2008	5w



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