Future Network and MobileSummit 2010 Conference Proceedings
Paul Cunningham and Miriam Cunningham (Eds)
IIMC International Information Management Corporation, 2010
ISBN: 978-1-905824-18-2

Link Group Management for Carrier-Grade Wireless Mesh Networks

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Abstract: Their distributed nature makes mesh networks easy to deploy and robust against node and link failures. However, distributing functionality adds high signalling overhead and delays. Forming resource clusters in wireless mesh networks is a well-known concept to alleviate these issues. This article describes a link group system for carrier-grade wireless mesh networks that provides absolute QoS guarantees. In order to support heterogeneous wireless mesh networks, the system interface of this link group system is implemented as a technology independent interface. Performance evaluations show a good fairness without requiring per-flow queuing, a good overall system performance, and small packet delays in multi-hop setups, which makes these link groups an important component of carrier-grade wireless mesh networks.

Keywords: Wireless Mesh Networks, Resource Management, System Architecture

1 Introduction

Wireless mesh networks are quick and simple deployable networks when no extreme optimization of the radio resource usage is needed. Typical use cases for such networks are short-term deployments and deployments in challenging environments such as disaster areas after earth quakes or tsunami catastrophes. Cellular operators can profit from such fast deployments in emerging markets, under unstable political situations, in case of peak demands, e.g., large events such as the Olympic Games, and in environments where no cable infrastructure is possible, e.g., among aircrafts on trans-continental flights [1] and among ships on sea lanes [2].

Current major examples of wireless mesh network technologies [3, 4] are the IEEE 802.11s draft standard [5, 6] to build mesh networks on top of IEEE 802.11 systems, as well as community projects, such as Roofnet [7] and Freifunk [8] to build wireless mesh networks at the network layer. Routing protocols for these technologies origin from mobile ad-hoc network (MANET) research, and are decentrally organized. Examples are AODV [9] and OLSR [10]. In their basic versions, these protocols place flows based on a shortest path strategy by evaluating the hop count. QoS aware flow placement can be achieved when link load measures as the Expected Transmission Time (ETT) and the Expected Transmission Count (ETX) are taken as routing metric. However, absolute QoS guarantees under high load situations can hardly be given owing to a lack of state and control in the network.

Pure service class-based packet networks with an Internet-style drop-tail queuing and TCP-like flow control are proved to miss the requirements of service predictability and a sufficient user separation in such environments [11], which is contradictory to typical service models of operators. Gerla and Tsai [12] promised to solve this issue with a connection-oriented model for wireless mesh networks based on assigned resources at each link using TDMA MAC protocols in combination with fast channel reservation mechanisms. This approach promises to solve the fairness issue and supports absolute

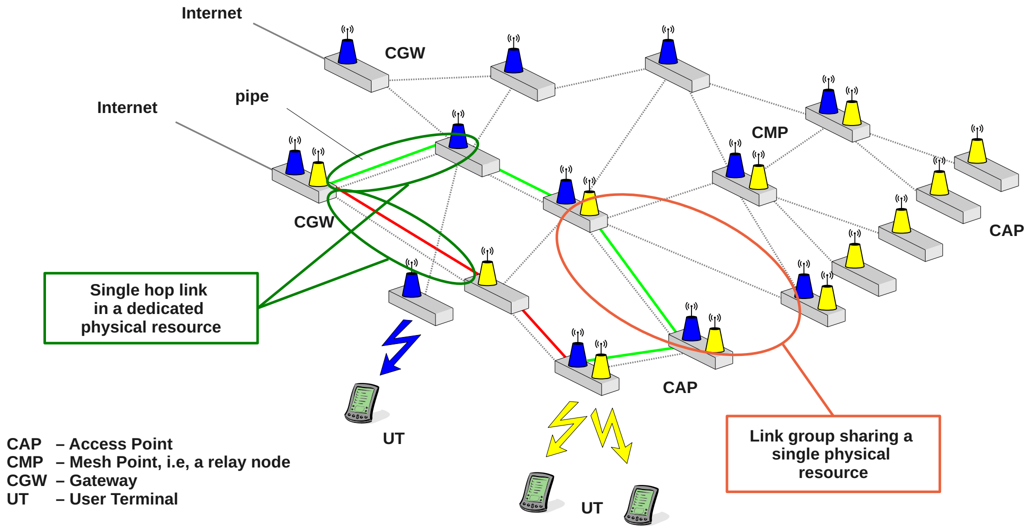


Figure 1: Example mesh topology with heterogeneous link technologies and user terminals being attached via dedicated resources. One link group as well as two isolated point-to-point links are highlighted. Pipes are formed using label-switching.

QoS guarantees at the cost of management overhead and an inflexible assignment of resources to flows. In this paper, a concept of resource management in clusters with fully flexible resource distribution among nodes inside the clusters using standard MAC technologies is proposed. The major design choices are

- to operate on connections inside the mesh based on label-switched flows.
- to have a centralized resource management
- to do shaping of user traffic at the ingress nodes of the mesh network.

When analysing the usage scenarios, it is easy to detect cases where mesh networks need to span different environments, including short- and long haul outdoor segments as well as indoor parts. Since all current wireless technologies are known to be designed for special environments, multi-technology support is a further feature of the proposed link group system integrating different link technologies, such as IEEE 802.11 with DCF and PCF support, IEEE 802.16, and DVB-T, below one mesh management.

In this article we present the proposed link group management system as a key component of heterogeneous carrier-grade wireless mesh networks. Furthermore, we show performance studies necessary to take design decisions for link group implementations. The article is structured as follows: In Section 2, the end-to-end concept of the EU FP7 project CARMEN (CARrier-grade wireless MEsh Networks) is presented, which is the environment for the present work. In Section 3, the link group system architecture and link abstraction concept are detailed. Finally, performance considerations for this type of link group management are presented in Section 4.

2 End-to-End Concept

This section provides an overview of the CARMEN end-to-end concept for traffic management; more details can be found in the project's architecture deliverables [13, 14].

All in all, we can classify the proposed mesh architecture to be a backhaul mesh with fixed mesh points. Figure 1 depicts an example mesh setup with CARMEN Access

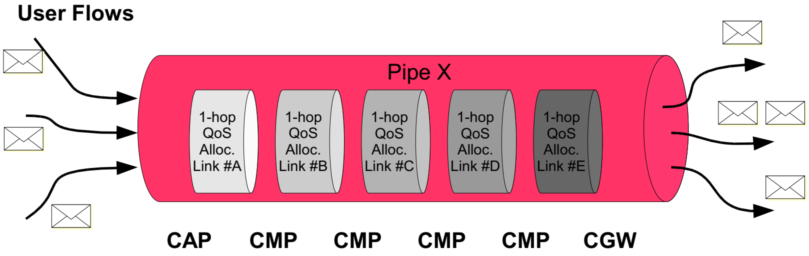


Figure 2: 3-tier traffic handling model showing user flows being mapped to a pipe of single hop packet forwarding functions supporting service level agreements

Points (CAPs), CARMEN Mesh Points (CMPs), and CARMEN Gateways (CGWs) as mesh nodes. CAPs and CGWs are mesh nodes with additional functionalities, such as ingress- and egress points of user flows and a mesh resource management. As in many current mesh networks, user terminals (UT) are attached to the mesh network via access points with dedicated interfaces.

A basic concept of the proposed mesh architecture are *Pipes*. Pipes are connections through the mesh networks and perform traffic handling based on label switching. This allows multi-path traffic routing for traffic between any two nodes in the mesh and provides the necessary information for QoS enhanced packet handling at each hop. Pipes are used for transporting user traffic as well as mesh-internal signalling traffic. User traffic pipes are formed at the ingress and egress points of the mesh network, i.e., at the access points and the gateways, and are aggregates of user flows of multiple users being attached at an access point. A pipe is implemented as a concatenation of single-hop packet transmissions, as this is depicted in Figure 2. Service level agreements (SLAs) for pipes are based on one-hop service level agreements at each hop.

Pipes are installed by the mesh management at a time scale between minutes and hours. We consider this to be a reasonable assumption since (1) the mesh topology is not expected to change significantly over time and (2) pipes are expected to have throughput requirements that are slowly changing. The latter expectation is based on the assumption that pipes carry mesh-internal signalling traffic or user traffic aggregates, which are expected to have semi-static throughput requirements and a limited burstiness owing to multiplexing gains.

Placing of pipes takes current resource allocations and capacities inside the mesh network as well as service creation profiles into account by not overbooking resources. User flows will be admitted at mesh ingress points to pipes according to pipe capacities and user profiles. The amount of resources allocated to each pipe and where a pipe will be placed in the mesh network is determined by a Capacity Management Function (CMF) and a Pipe Computation Element (PiCE). The latter two functions, together with the mesh self-configuration function (SCF), form the so called *Mesh Management*, which is located at the mesh gateways. The management functions of the CARMEN end-to-end concept, especially those of the mesh resource management and the pipe maintenance, are put into practice as technology-independent functions. They form the so-called *"Mesh Domain"* of the CARMEN layer model.

A mesh network is a graph of links, with links having capabilities, such as capacity, load, and link-group membership. *Link Groups (LG)* are defined as a set of links between nodes sharing the same physical resource, e.g., spectrum, time, or code, and which are

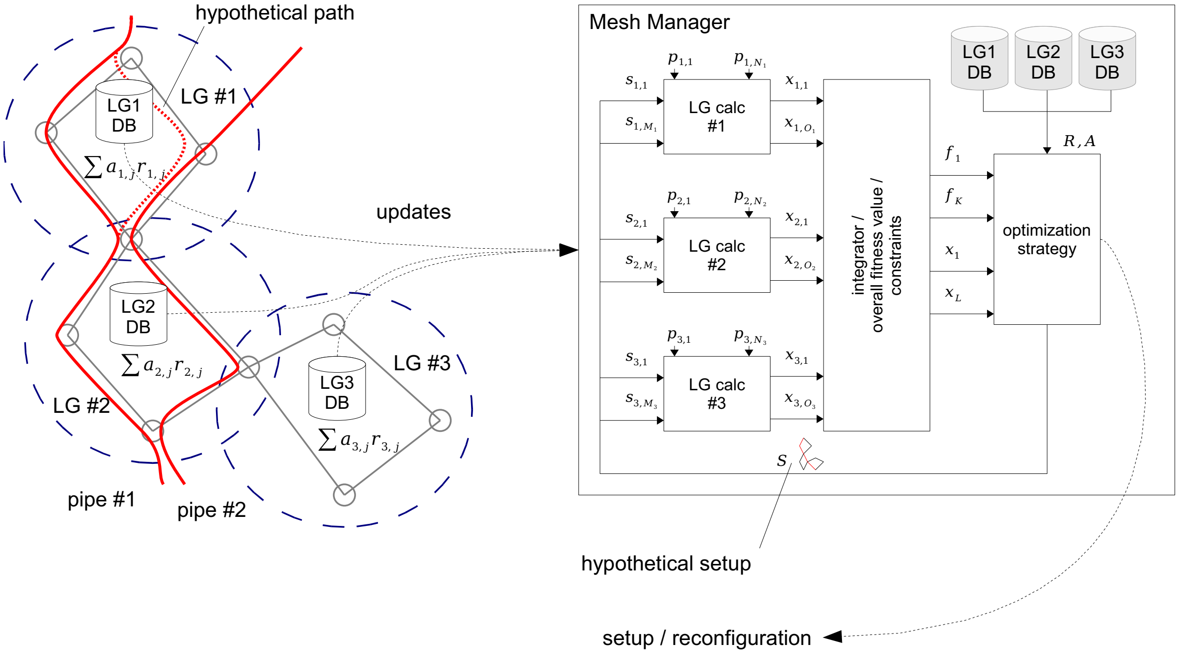


Figure 3: Signalling flows in a setup with 3 link groups and one mesh manager

using the same local MAC protocol. For the mesh integration of such link groups, they are enhanced with a *Link Group Management (LGM)* function, which is local to the link groups. The interaction between decentralized link groups and mesh managers is visualized in Figure 3, which depicts the signalling flows between these units. Link group parameters and state information of admitted one-hop SLAs are signalled towards the mesh management and setup commands are conveyed in the opposite direction.

The pipe computation element is able to pre-calculate hypothetical load situations for link groups when searching for an "optimal" route for a new pipe or when re-arranging pipes for a global mesh optimization. Pre-calculations of hypothetical load situations of link groups and link group admission control calculations are done off-site from the link group perspective without the need for any further signalling between the mesh management and the link groups, which would not be possible for performance and scalability reasons. After a successful placement of a pipe, the new one-hop SLAs will be installed at the link groups or existing SLAs will be updated. In cases where no new setup could be found, a pipe setup request will be rejected from the mesh manager.

3 Link Abstraction and Link Group Management

The described link abstraction concept includes as major components a QoS enhanced single-hop packet forwarding function, a service access point for manipulating links, and a technology-independent resource model. In this section, the architecture of mesh nodes and the link group management function implementing the management interface are described and the resource model is introduced, which we consider to be the major components of link groups.

3.1 Node Architecture and Abstract Interface

Figure 4 depicts the building blocks of a CARMEN mesh node including the mesh domain, which was introduced in Section 2, and the link domain. The *CARMEN Abstract*

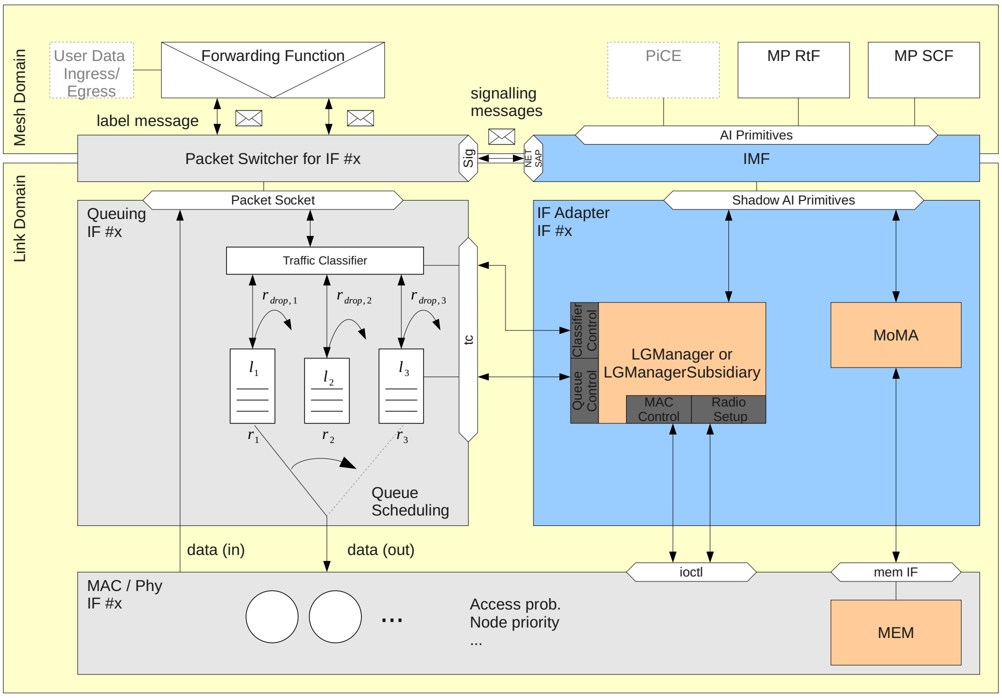


Figure 4: Node architecture of mesh points with interface control units for mesh control

Interface (AI) is the control plane service access point (SAP) for manipulating links and link groups. It supports service primitives for physical topology detection, interface configuration, link group manipulation, and resource allocation and is build by an *Interface Management Function (IMF)* and multiple *Interface Adapters (IA)*. The interface management function provides a forwarding and transaction service for issued service primitives. In the interface adapters—there is one instance for each network interface of the mesh node—we implement the technology-specific service primitives and with it the mappings between the technology-specific and the technology-independent link representation.

The data plane of mesh nodes depends on the MAC technology of link groups and even for the same MAC technology various implementations are possible. Packet handling inside link groups might be organized with connection orientation, e.g., in some WiMAX link groups, or a as class-based packet forwarding, e.g., in IEEE 802.11 systems. The data plane that is depicted in Figure 4 is that of a generic link group architecture with a generic queuing system. This data plane will be used for the system design and performance considerations in section 4.

3.2 Link Group Management

The technology-specific management of link groups is implemented inside the interface adapters. It includes a resource management for the link group and an admission control for one-hop SLAs. Depending on the link group implementation, this management might include tuning of node-specific queuing and MAC parameters as well as installing connections among nodes. In the current CARMEN implementation, one node of each link group is elected to be the master for general tasks including the bookkeeping and admission control for the link group. However, distributed implementations appear to be feasible. In the centralized parts of the LGM function, LGM subsidiaries in the

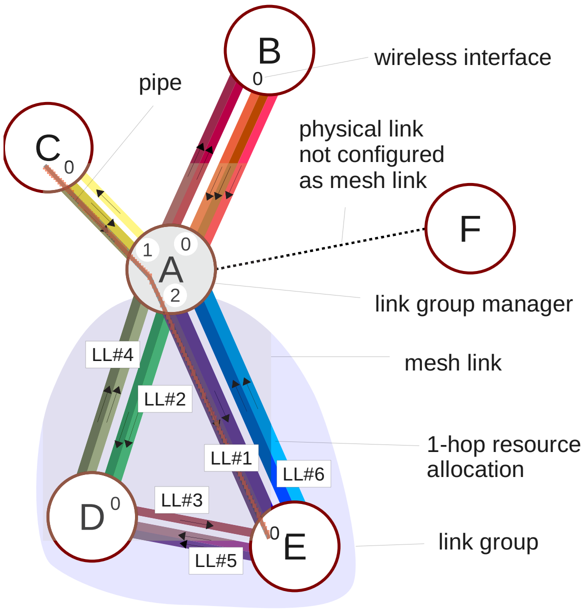
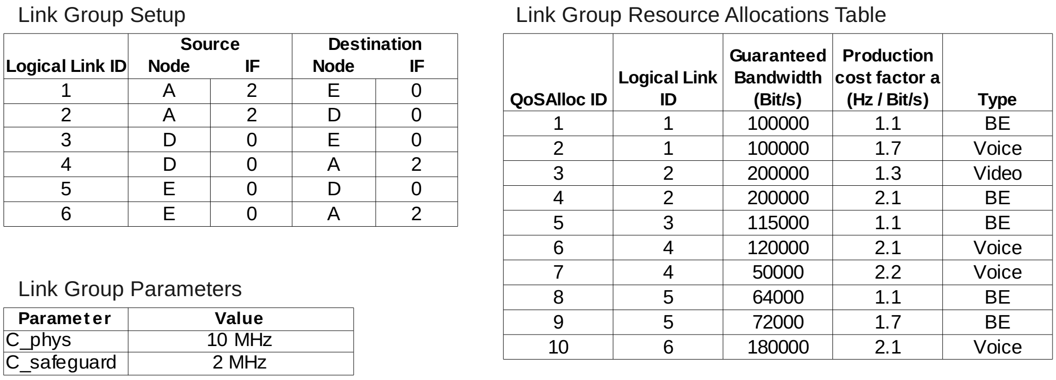


Figure 5: Link group in a multi-hop scenario. The nodes A, D, and E are forming a link group. Unidirectional logical links LL#1 to LL#6 are the links of the link group. One-hop SLAs are represented as colours.

non-managing nodes of the link group are issuing local setup commands on behalf of the manager, for which a link group specific signalling has to be implemented.

Figure 5 depicts an example topology of a link group with a decentralized MAC. Node A of this setup is elected to be the link group manager. Figure 6 depicts the tables with management information maintained by the link group manager. This includes a graph description of the logical links, a table with overall link group parameters, and a resource allocation table with the resource allocations at the logical links. The link group setup table is generated from tracking the self-configuration process. The link group capability table includes local knowledge and settings of the link group, e.g., the link group capacity. The resource allocation table is maintained to track setup, change, and release requests for one-hop SLAs from the mesh management.



Link Group Setup

	Source		Destination	
Logical Link ID	Node	IF	Node	IF
1	A	2	E	0
2	A	2	D	0
3	D	0	E	0
4	D	0	A	2
5	E	0	D	0
6	E	0	A	2

Link Group Parameters

Parameter	Value
C_phys	10 MHz
C_safeguard	2 MHz

Link Group Resource Allocations Table

QoSAlloc ID	Logical Link ID	Guaranteed Bandwidth (Bit/s)	Production cost factor a (Hz / Bit/s)	Type
1	1	100000	1.1	BE
2	1	100000	1.7	Voice
3	2	200000	1.3	Video
4	2	200000	2.1	BE
5	3	115000	1.1	BE
6	4	120000	2.1	Voice
7	4	50000	2.2	Voice
8	5	64000	1.1	BE
9	5	72000	1.7	BE
10	6	180000	2.1	Voice

Figure 6: Management information for link groups. This information is maintained and measured by the link group managers and synchronized with mesh managers.

3.3 Link Group Resource Model and Link Group Admission Control

Wireless cells are known to not have a constant transmission capacity at the network layer. The observed network layer performance depends on environmental parameters, such as the distribution of nodes in the cell, channel conditions, traffic distribution, and interference. It also depends on how the MAC scheduler(s) assign resources to transmissions. For a running system, the resource consumption x in a cell can be determined by evaluating information from MAC schedulers in that cell. Not that exact, but more flexible, on average estimations of the physical resource requirements in a cell can be accomplished by concluding from measurements of transmission properties to the physical resource need. Transmission properties are transmit power, path loss, interference level at the receiver side, and channel types and result in an signal to interference ratio (SINR) at the receivers. Now, performance models for radio links allow a mapping between the physical resource consumption and the network layer performance taking modulation and coding scheme performance and the overhead for signalling and protection mechanisms into account. Since this mapping expresses the physical resource consumption for bit transmissions, it will be denoted as production cost factor, which we write as a.

The production cost factors depend on radio properties of links as well as traffic type specific overheads as ARQ/HARQ and coding. Based on these considerations, we consider them to be individual for each one-hop SLA, which we write as a_i. As production cost factors include technology-specific details, they will be determined by the link groups.

To calculate the overall resource consumption x of a link group, we aggregate the resource consumptions of all one-hop SLAs of that link group. The calculations are based on rates. Following the paradigm of not overbooking links on average, this resource consumption directly leads to an admission policy for one-hop SLAs of

$$x = \sum_{\forall i} a_i \cdot r_i \leq C_{phys} - C_{margin} \tag{1}$$

with C_{phys} being the available physical resource rate of the link group and C_{margin} being a spare capacity for enhancing service quality by respecting temporal fluctuations and bursty traffic conditions.

In the CARMEN project, technology mappings for link group capacities and production cost factors have been done for different Phy layers and MAC protocols. Considered systems were IEEE 802.11 DCF, IEEE 802.11 with TDMA enhancements, IEEE 802.16, and DVB-T. Some of the technology-mappings are currently under evaluation in a prototype setup. Further considerations on non-linear MAC behaviour using linearization techniques can be found in [15, 16].

By introducing production cost factors a as a generic mapping between physical resource consumption and bit transmissions, a technology-independent resource model and admission control rule could be re-established. The technology-specific parameters a_i, C_{phys}, and C_{margin} are determined by the LGM function inside the link groups and are signalled to the mesh managers, as this has been outlined in section 2 with the advantage of allowing admission-control calculations for link groups off-site from the link groups at mesh managers.

4 Link Group Performance Considerations

The service contract between link groups and the mesh management assumes (1) that rapid changes of the production cost factors a_i and the safeguard capacity C_{margin}, as well as bursty packet arrivals are treated by the link groups and (2) that long-term changes are signalled to the mesh management to improve the overall mesh performance by pipe re-arrangements. Mechanisms inside the link groups for maintaining one-hop SLAs are queuing disciplines, MAC tuning, e.g., setting node weights, and maintaining safeguard capacities. To find the optimal implementation for link groups, several performance studies taking bursty traffic conditions and fluctuating radio links into account are required. Examples are:

- optimizing the tradeoffs between service stability and the amount of bookable resources by setting C_{margin}
- evaluating the influence of uncontrolled radio emissions in unlicensed spectrum
- comparison of different packet handling concepts including connection oriented packet handling and class-based queuing

In the following, a simulation study of the per-node queuing system and the overall benefit of the resource management system is presented. Figure 7 depicts the used mesh topology with 6 mesh nodes sending traffic at a given rate towards a gateway using pipes. The whole topology fits into one link group. To limit interference to a shorter region of the overall network, multi-hop pipes towards the gateway are preferred over single-hop transmissions. Further radio effects are not taken into account. Pipe sources offer traffic at a given rate with negative exponential packet inter-arrival times without flow control mechanisms for detecting congestions along the paths. Since the 6 pipes consume in total 12 resources, i.e., there are 12 hops inside the link group, the link group will be loaded when each pipe offers a traffic of 1/12 of the link group capacity at the network layer.

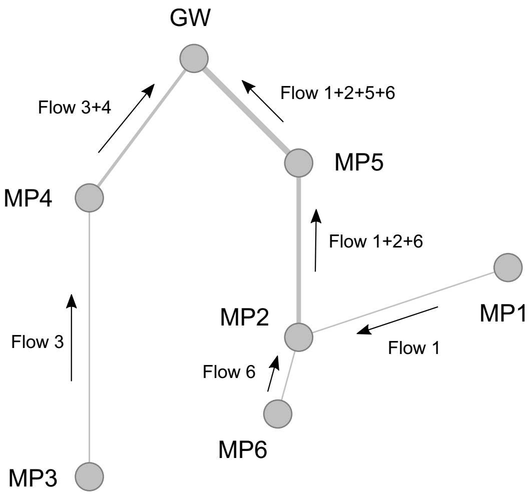
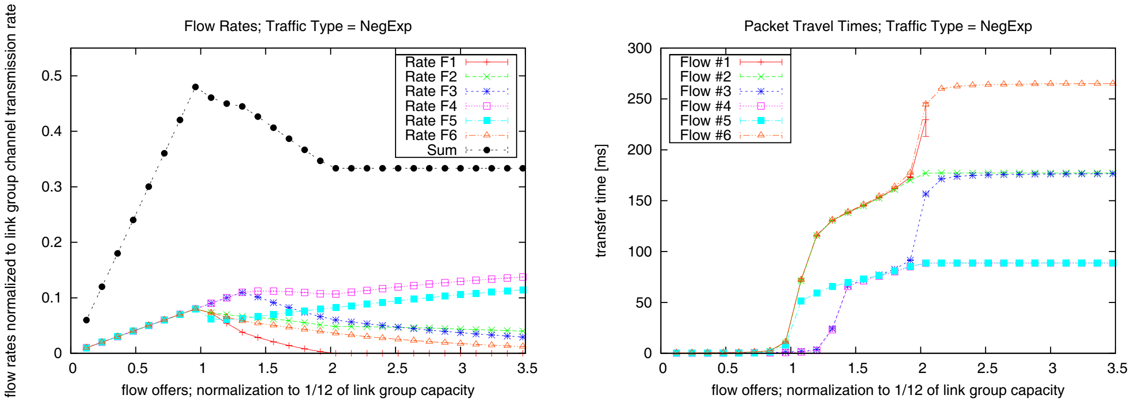


Figure 7: Simulation topology for multi-hop traffic inside a link group

We set up the link group as a generic link group and the media access of the nodes is organized in a fair manner among the nodes using a round-robin scheduler. Flows inside the nodes are not weighted and are treated using a single service class with drop-tail queuing. The end-to-end pipe performance results from all single-hop packet forwarding delays and the available bitrates. Figure 8(a) depicts the resulting pipe rates in relation to the offered load. It can be seen, that the pipes receive the required service, unless the total offered load exceeds the link group capacity. When reaching and exceeding this point losses rise sharply, as it can be seen when extrapolating the linear growth of the rates and comparing it with the observed rates. Also the overall performance of the link group, which is the sum of all pipe rates, starts to decrease at this point, which is a result of packet drops along the transmission paths after having consumed resources. Furthermore, it can be seen that under overload conditions, shorter pipes are preferred



(a) Throughput (b) Delay

Figure 8: Multi-hop flow performances in a generic link group showing good/bad behaviour in terms of fairness among flows and delays under normal/overload situations.

over pipes with more hops. This is owing to treating aggregates and local traffic equally at each hop, which is unfair compared to a pure fair treatment of pipes. This findings consistently match to those of Jun and Sichitu [11] when evaluating queuing concepts for multi-hop networks.

Similar to results on flow rates, Figure 8(b) shows that under a controlled load situation, the link groups have a quite good delay performance. Almost no delays can be observed except the pure packet air times. When overloading the link group, i.e., the offered load is above 100%, the delays increase rapidly and are then defined by the buffer size at the bottleneck links and the channel capacity.

From the results, the following can be concluded: (1) in controlled load situations, a per-node weighting and a per-pipe queuing is not that important. However, under overload situations, as this might appear under bursty traffic conditions, this might be different. (2) Under controlled load situations, delays appear to be negligible compared to typical 200 ms delay requirements for voice traffic.

5 Summary and Conclusions

The CARMEN link group concept has been presented and related to a mesh end-to-end system aiming at strictly managing resources inside wireless mesh networks. For supporting heterogeneous wireless mesh networks under a homogeneous mesh management system, the link abstraction concept including the CARMEN Abstract Interface (AI) and an abstract resource model capable of modelling wireless point to multi-point system have been introduced. Mappings of the AI service primitives and the abstract resource model to various link technologies have been outlined. Link group parameter dimensioning tasks necessary to assure service level agreements for one-hop transmissions have been indicated and design tradeoffs have been identified.

Based on a generic link group, performance studies have been presented giving relevant design hints for technology-specific link group implementations and demonstrating the good mesh performance when using managed link groups. Especially the good fairness behaviour and the good delay performance under controlled load situations could be demonstrated.

Acknowledgements

I would like to thank Stefan Valentin for valuable suggestions. The system architecture described herein is not solely a result of the author's work and also includes results of joint project discussions and contributions of other partners. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement N° 214994.

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