Performance Enhancement of Inter-Subnet Communication in HiperLAN/2 Home Environments

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Abstract

With HiperLAN/2 (H/2), the European Telecommunications Standards Institute (ETSI) designed a high bit rate wireless communications system for the 5 GHz frequency band. Beside infrastructure based networking, H/2 provides the concept of a one hop ad hoc network topology, called Home Extension, whereby each single subnet is centrally coordinated. The objective of a novel forwarding technique in the frequency domain, introduced in [1] and [2] for the first time, was to overcome the restrictions of the one hop ad hoc configuration and to extend it to multihop connectivity. Although simulations showed convincing results for throughput and delay characteristics, all potentialities of gaining performance have to be taken into account to fully support Quality of Service. This paper describes an improved concept of H/2 MAC Scheduling specifically adapted to the requirements of *inter-subnet* communication as well as the benefits reached by coordination and synchronization of forwarders.

1 Introduction

HiperLAN/2 was created as a platform for wireless Internet and Multimedia services [4]. It provides transmission rates of up to 54 Mbit/s by using Orthogonal Frequency Division Multiplex for modulation. The Medium Access Control Protocol (MAC) is organized in a central and connection oriented way based upon time division multiple access and time division duplex transmission to support uplink, downlink and direct link connections [5]. Specific Quality of Service (QoS) requirements may be selected per connection [6]. All signaling functions, e.g. for establishment of user connections, are handled by the Radio Link Control Protocol (RLC) [7]. On top of the Data Link Control Layer (DLC) covering MAC, RLC, and Error Control, convergence layers adapt to transport standards like Ethernet and IEEE 1394.

To extend the H/2 DLC basic standard designed for a cellular infrastructure, the Home Environment Profile (HE) of H/2 offers ad hoc communication to allow operation in plug-and-play manner [8]. In the current HE specification, a one-hop ad hoc connectivity is provided if all Wireless Terminals (WT) are in transmission range and one WT is available to take the role of a Central Controller (CC) [9]. In order to increase the applicability of H/2 to multihop networks, a forwarding technique operating in the frequency domain has been proposed that is described in detail in the following chapter. Since each forwarder is suggested to periodically switch among the frequency channels of subnets it connects, a coordination and synchronization of forwarders such that they can operate in parallel or that forwarders to different subnets can communicate directly is expected to improve efficiency. This paper introduces concepts to enhance the performance of multihop ad hoc networks by the means of forwarder coordination and specific MAC scheduling. Various multihop ad hoc scenarios are presented and investigated both for synchronous and asynchronous operation of forwarder nodes. The simulation results are compared dependent on the route length in hops.

2 Forwarding in the Frequency Domain to Connect Subnets

Interconnection of H/2 subnets aims to enable WTs of different one-hop networks to communicate. Since adjacent subnets operate on separate frequency channels according to the Dynamic Frequency Selection (DFS) to minimize interferences, a forwarding in the frequency domain is required. **Fig. 1** gives an example of such a multihop ad hoc scenario with two single subnets connected by terminals able to operate in two or even more adjacent subnets alternating, so-called *Multiple-frequency Forwarder* WTs (*MF*-WTs).

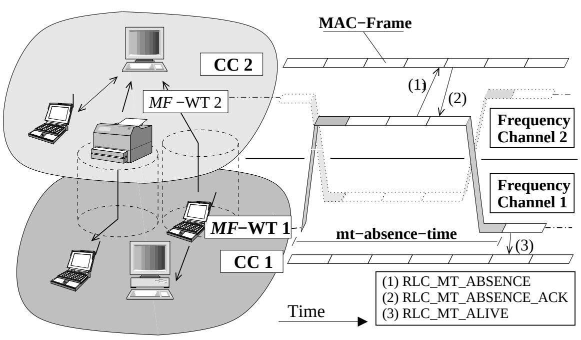

Figure 1. Communication Across Subnets

In order to select *MF*-WT candidates, DFS measurements are evaluated. The appropriate terminals are then allowed to associate to the other subnets in addition. If such association attempts are successful, forwarder operation can be started. *Inter*-subnet data exchange is realized by the periodical presence of an *MF*-WT at each subnet for negotiated time intervals. These presence phases are intermitted by absence phases to continue communication with the other subnet(s). Therefore, the RLC functions MT_Absence and MT_Alive are used in a modified way. Since an *MF*-WT provides direct radio contact only to WTs of one subnet at a time, it emulates WTs of the other subnets and caches all data it is receiving for them. The operation of one (two) *MF*-WTs associated to the CCs of two adjacent subnets is shown in Fig. 1 in detail. A terminal selected to be *MF*-WT is first present in subnet 2. It leaves this subnet by transmitting the message *RLC_MT_ABSENCE* (1) to CC2. When the *MF*-WT then receives the acknowledgement (2), the radio link is intermitted, and the absence timer starts from the following MAC frame on. After switching frequency, that is assumed to last about 1 ms [9], the Broadcast Channel (BCH) sent by CC1 has to be detected and decoded by the *MF*-WT to synchronize. In case it awakes in subnet 1 earlier than expected, its presence is announced to the CC by transmitting an *RLC_MT_ALIVE* (3) message via the Random Channel (RCH). Otherwise, the *MF*-WT is scheduled automatically and just starts transmission. To return to subnet 2, the MT_Absence procedure is executed again. This sequence is repeated continuously.

3 Forwarder Coordination and Synchronization

3.1 The Two-Subnet Constellation with Alternative Forwarder Candidates

A single forwarder in the frequency domain is limited due to a couple of reasons. On one hand, each frequency switching and synchronization event requires about one MAC frame in time. On the other hand, the *MF*-WT is periodically unavailable in a subnet for a certain absence period. A comparison in [1] has shown that *inter*-subnet-throughput under best conditions reaches approximately 44% of the maximum possible *intra*-subnet-throughput.

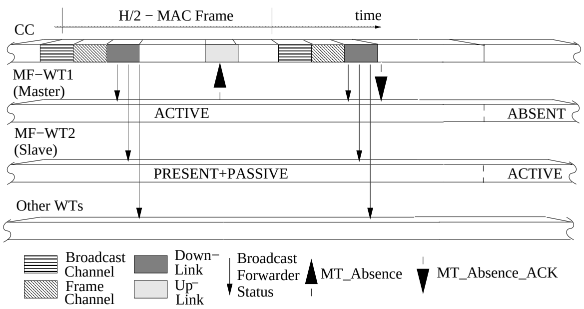

Figure 2. Master-Slave Coordination of Forwarders

However, the proposed forwarding technique is very flexible and, an important aspect, it does not prevent from running several forwarders in parallel, even for the same pair of adjacent networks. This induces that nearly all constellations of M subnets connected by N forwarder nodes are at least theoretically possible.

For the concrete realization of forwarding in parallel, it has to be considered that *MF*-WTs concurrently receiving and delivering data for the same *inter*-subnet link inevitably will forward the same PDUs. Beside doubled and corrupted data at the receiver, inconsistencies in the error control will be consequences. Therefore the efficiency can be expected to be perhaps even worse than with a single forwarder. The conclusion is to coordinate all forwarder candidates in a master-slave manner such that only one *MF*-WT takes an active part (master) for each pair of adjacent subnets. Another *MF*-WT candidate (slave) is just activated when the master leaves the subnet, see **Fig. 2**. To implement this technique, the CC, having access to all subnet related information, is proposed to broadcasts a novel “FORWARDER_STATUS_MAP” RLC message in the downlink. This message lists all terminals selected to be active forwarders for the next MAC frame in the order of the destination subnets’ frequency. Whenever a forwarder switches to an adjacent subnet, it has to evaluate the status message and to operate as common WT until it is selected to become active and to replace the previous *MF*-WT.

With such a CC controlled forwarder coordination, it is possible to link two subnets by several forwarders - asynchronous or synchronous as well. Latter can be achieved if the CCs of adjacent subnets establish a CC-to-CC connection based upon the asynchronous *inter*-subnet link to exchange timing information. Please note that no exact frame synchronization is meant, but an adjustment of frequency switching times within a range of ± 1 ms. An example given in Fig. 1 shows two WTs located in the overlapping of two subnets. When absence and presence periods are synchronized in the way that alternating one *MF*-WT is available per subnet, I call it “Alternating Forwarders”, a more time-continuous interconnection can be achieved resulting in substantial improvements for throughput and delay [2].

3.2 Configuration of Three Subnets Adjacent in Pairs

Considering another configuration, the composition of three subnets, requires to distinguish some variations. If two subnets have poor or no radio access to each other, a third subnet could act as bridge between both. For sure, this constellation only makes sense if the transit route with ≥ 3 hops shows better characteristics than the direct two-hop link. In case of a second constellation with each subnet having a direct radio link to all adjacent subnets, alternative paths to the destination will be the prevailing difficulty. Since propagation delay increases with route length, see also Fig. 12, the CCs should then use the MAC Scheduling to always prescribe the shortest route from source to destination with a minimum number of intermediate forwarders. In section 3.3, a third variation is explained that can be seen as special case of the previous one, assuming three subnets with joint coverage area.

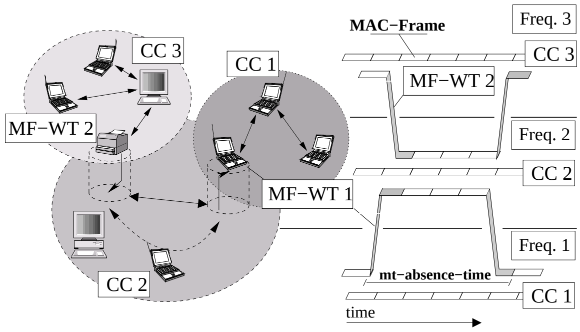

Figure 3. Multihop Scenario of Three Subnets Adjacent in Pairs

A three-subnet multihop formation corresponding to the first variation is depicted in **Fig. 3** consisting of two outside subnets and one bridge subnet. It is conceivable that a source terminal in subnet 1 first transmits to the forwarder MF-WT1. This forwarder delivers the data either to the CC of subnet 2 or, if it is available, to the second forwarder *MF*-WT2 providing access to the destination WT. The CC is required to relay inter-subnet PDUs whenever the *MF*-WTs do not have direct radio access to each other due to operation on different frequency channels or frequency switching phases. Even for this scenario, a synchronization of forwarder nodes is advantageous such that both forwarders are present concurrently in subnet 2. Thus, CC relaying is avoided resulting in three-hop routes, only, equivalent to reduced packet delay.

3.3 Triple Subnet Scenario with Joint Coverage Area

Last but not least, a concept of interconnecting three subnets by a single or just two synchronized forwarders is described that implies the existence of a joint coverage area for all subnets. The benefit of this approach is the route length limitation to two hops, see **Fig. 4**. In order to force such a constellation, a quite robust PHY mode, e.g. BPSK ½, may be needed for all connections to the *MF*-WT dependent on the radio conditions. This *inter*-subnet configuration is not expected to be very efficient, however, it will be a solution if there is no alternative due to a low concentration of WTs capable of forwarding among the subnets.

If two or more forwarders are located in the joint coverage area, a performance enhancement will be reached if the *MF*-WTs are synchronized and coordinated to be alternating present at the involved subnets. Therefore, a frequency hopping sequence should be negotiated for each *MF*-WT similar to the modus operandi of Bluetooth devices. Bluetooth is another wireless LAN standard supporting ad hoc communication in so-called Piconets by frequency hopping whereby each terminal is assigned a hopping sequence corresponding to its device address intending to minimize interferences [10]. This idea could be taken over for H/2 forwarders in the frequency domain.

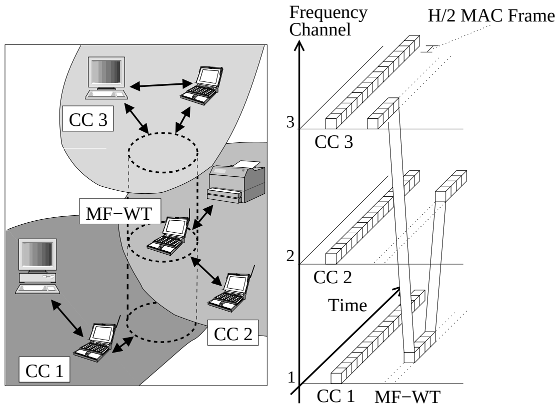

Figure 4. MF-WTs Connecting 3 Subnets

4 Improved MAC Scheduling

In order to optimize the performance of traffic across subnets, several aspects are worth investigation. A special focus is set to MAC Scheduling of multihop traffic. In the following, an overview is given on well-known algorithms. Then, algorithms designed to support H/2 multihop ad hoc network communication are presented.

4.1 H/2-MAC Scheduling Algorithms

Static Resource Allocation guarantees transmission of a specified number of Protocol Data Units (PDU) per MAC Frame. Therefore, the capacity is negotiated during the connection setup phase and may be changed by a connection modify procedure. A disadvantage is the low flexibility under changing capacity demands. H/2 provides two corresponding functions in the standard - Fixed Slot Allocation (FSA) [7] and Fixed Capacity Agreement (FCA). FSA continuously reserves a fixed number of slots at a certain position in the MAC frame and is intended for time-critical services like e.g. the IEEE 1394 clock synchronization. FCA is more flexible in the sense that resources can be reserved periodically every *N* frames [5] and that the position within the MAC frame may vary.

Dynamic Resource Allocation algorithms are based on so-called Resource Request (RR) & Resource Grant (RG) signaling messages. The H/2 specification do not prescribe certain MAC algorithms, so that several methods known from the theory of queuing systems [11] and computer networks [12] can be applied. The Non-exhaustive Round-Robin approach assigns each user connection a share of one LCH timeslot in the MAC Frame unless it is filled up or all resource demands are satisfied, see also [13]. The Exhaustive

Round Robin algorithm instead serves a first connection completely, before the second and third etc. connection is considered. Longest Queue Scheduling - preferring connections with the highest amount of data pending - is also worth mentioning here.

Priority-based Scheduling combines Static and Dynamic Resource Allocation. Since H/2 provides priority levels, it is possible to differentiate regarding the scheduling strategy to be applied for a connection. In [13] a two-stage priority scheduling is presented assigning fixed capacity to time-critical services and scheduling lower prioritised services dynamically.

4.2 Remaining Resource Scheduling

An extensive examination of scheduling and resource request algorithms for H/2 multihop ad hoc networks showed a weakness of dynamic resource allocation. If the capacity for *inter*-subnet connections is requested from an *MF*-WT by RRs and then granted by the CC in one of the following MAC Frames, at least one MAC frame is not efficiently utilized.

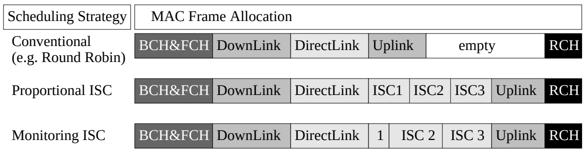

Figure 5. MAC Frame Allocation with Different Scheduling Strategies

Proportional <u>I</u>nter-<u>S</u>ubnet <u>C</u>onnections (<u>ISC</u>) is an idea to overcome the shortcomings of common resource request mechanisms. Proportional ISC takes into account that especially the first MAC frame, after an *MF*-WT has switched to another subnet, is filled only partially. Although PDUs to the *MF*-WT can be scheduled by the new CC in time, data from the *MF*-WT must wait up to the reception of the RGs. This motivates an scheduling algorithm that becomes active if capacity is left in the MAC frame after all connections have been scheduled by conventional algorithms, like e.g. Round Robin. The remaining capacity is then equally shared among the *inter-subnet* connections, see **Fig.5**.

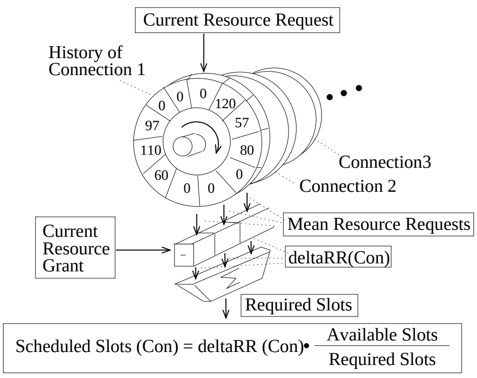

Figure 6. Concept of Monitoring ISC Scheduling

Monitoring ISC is another concept that extrapolates from the history of each connection the resources needed in the next MAC Frame. Compared to Proportional ISC that shows its strength with a homogeneous traffic load, Monitoring ISC is more efficient if the traffic loads for different connections diverge. The algorithm is depicted in **Fig. 6**. Per connection, incoming RRs are collected and stored in a ring buffer that can be adapted in size to system parameters like the *MF*-WT absence time. In order to calculate the resource demand of a connection for the current MAC frame, the mean value of all buffered RRs is compared to the resources already granted by a conventional scheduling algorithm. The residual demand (*deltaRR)* is computed for each connection. Considering all required and free slots, the available capacity of the MAC frame can be divided with respect to the expected individual requirements of each connection.

5 Performance Analysis

5.1 Simulation Scenario

In order to evaluate multihop ad hoc communication under realistic conditions, event driven computer simulations [13] have been performed. Two scenarios were considered dependent on the simulation focus. On one hand, a three room flat with nine wireless H/2 devices, see **Fig. 7**, was used to examine a two subnet constellation. Under the given radio propagation situation, the subnets overlap in the central room where two terminals selected to be *MF*-WTs are located. On the other hand, a scenario consisting of four rooms with three established subnets was used to value 3- and 4-hop connections with and without CC-relaying.

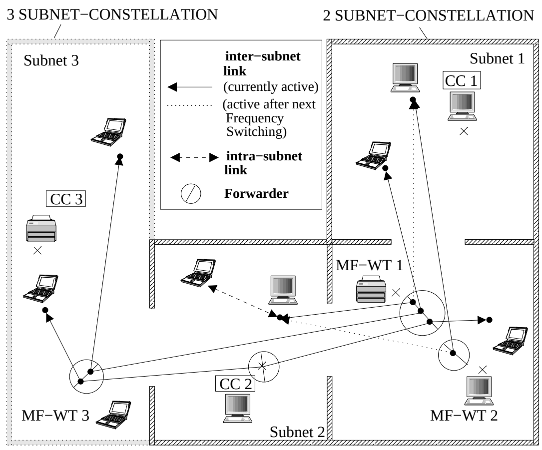

Figure 7. Multihop Ad Hoc Simulation Scenario

Since most H/2 devices belonging to one subnet are line-of-sight or in low distance, the highest possible PHY mode 64 QAM ¾ can be applied for all <u>D</u>LC <u>U</u>ser <u>C</u>onnections (<u>DUC</u>) with a low Packet Error Ratio. Per DUC various parameters, like unidirectional/bidirectional communication or different QoS requirements are adjustable. Load generators for Constant Bit Rate, MPEG video and Poisson traffic sources are available.

5.2 Throughput and Delay Characteristics with Remaining Resource Scheduling

In order to find out the performance capability of multihop communication based on forwarding in the frequency domain the *inter*-subnet throughput was analysed both for common Round Robin MAC Scheduling and Proportional ISC. In **Fig. 8**, the throughput characteristics for a constellation of both one single *MF*-WT and two coordinated *MF*-WTs are plot against the absence time parameter that is given in the unit of H/2 MAC Frames (2ms). From the resulting curves, it becomes obvious that the lower limitation of *mt-absence-time* can be reduced from 3 MAC Frames to 2 MAC Frames by application of Proportional ISC.

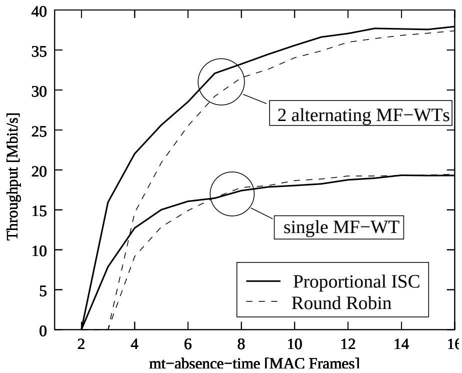

Figure 8. Throughput against Absence Time Plot

Beside maximum throughput, the end-to-end delay is the second characteristic parameter with high relevance regarding QoS requirements. Therefore, **Fig. 9** shows a combined representation of the results for maximum throughput and mean delay. Based on the curves, the set of possible operation points of the *MF*-WTs can be identified.

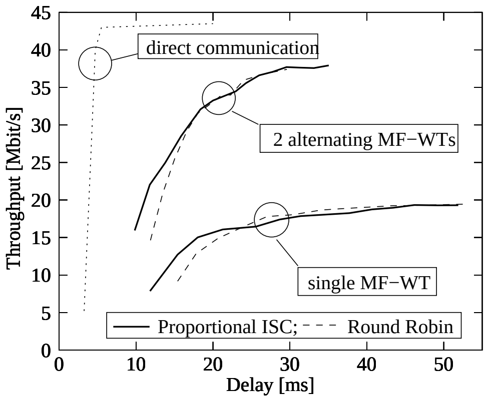

Figure 9. Throughput versus Delay

As already outlined, Proportional ISC is well applicable for homogeneous load conditions whereas Monitoring ISC is beneficial in the case of heterogeneous load situations. A comparison of both techniques is given in **Fig. 10** for 1 up to 3 bi-directional connections under equal and different load conditions whereby the absence-time is set to 5 MAC Frames. For the heterogeneous load distribution, the traffic load of the 2nd bi-directional link was set to one half, for the 3rd link to one quarter of the traffic offered to the 1st connection.

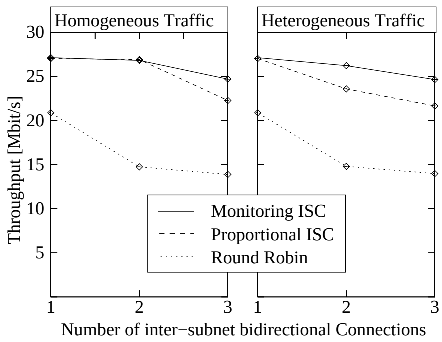

Figure 10. Comparison of Scheduling Strategies

5.3 Three-Subnets Scenario – Benefits of Forwarder Coordination

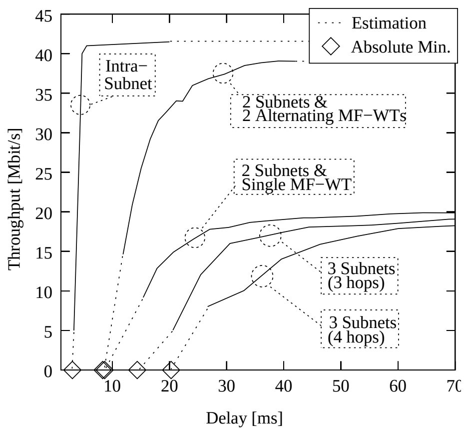

Figure 11. Performance of Multihop Traffic

When extending the scenario for a third subnet, two further types of *inter*-subnet connections are worthy to note. WTs of subnet 1 and 3, i.e. the outside networks being out of transmission range, can only reach each other via 3- or even 4-hop routes. If there is a perfect coordination between the two single *MF*-WTs, that connect the pairs of adjacent subnets, such that they are present in subnet 2 concurrently, a forwarder-to-forwarder connection is established resulting in a 3-hop route. Whenever there is only one *MF*-WT present in the transit subnet 2, however, the only reasonable solution is to use the CC as a relay station. In **Fig. 11** the performance characteristics of those 3- to 4-hop connections are depicted in the form of throughput vs. delay curves for Round Robin Scheduling. It turns out that especially the delay is affected by an additional hop via the CC.

For the examination of drifting single *MF*-WTs in a three-subnet scenario, the absence time was set to 10 MAC frames. From the graphical representation in **Fig. 12**, it can be seen that throughput and delay curves are periodic, i.e. after 18 MAC Frames the *MF*-WTs are synchronized again. Regarding the delay, a pure 4-hop route, resp. a drift of 9 MAC frames, shows a significant worse performance than the pure 3-hop route – corresponding to a drift of 0 or 18 MAC frames, whereas the throughput proves to reach nearly the same results for both scenarios. In the transition range, however, a rapid drop of the throughput to a minimum level of about 76 %, is conceivable.

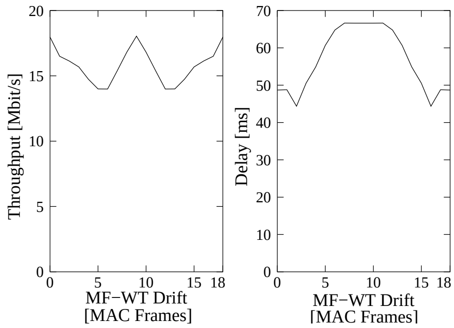

Figure 12. Forwarder Drift in a 3-Subnet Scenario

In order to resume the investigations, **Fig. 13** plots maximum throughput as well as mean and minimum delay against the route length in hops. One curve parameter is the number of forwarders connecting two adjacent subnets, i.e. either a single or two alternating *MF*-WT(s). For the second parameter, the absence time, three cases are considered – a delay optimised value of 5 MAC frames, a throughput optimised value of 15 frames and 10 frames in between.

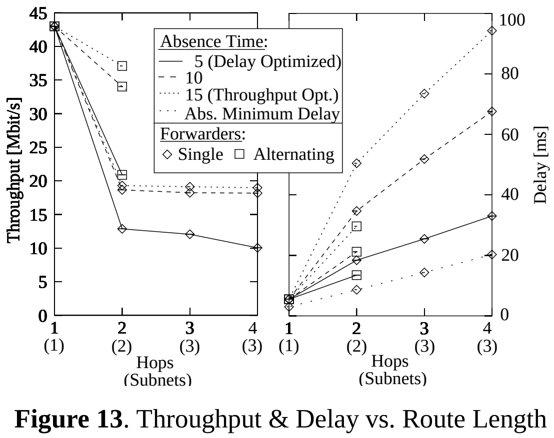

Figure 13. Throughput & Delay vs. Route Length

From the results shown, it can be concluded that an *MF*-WT should adapt the absence time parameter to the QoS demands of the traffic mix it serves. In case of time-critical services, a low absence-time shows a good delay performance even for 3- and 4- hop routes whereas the throughput is significantly reduced. Another interesting effect, that has to be explained, is the minor throughput decrease from 2- up to 4- hops. Considering the 3-hop scenario, for example, it can be found out that data on the two *inter*-subnet links are transferred in parallel inducing similar conditions as for 2-hop communication. A fifth hop, however, is expected to reduce *inter*-subnet throughput stronger. From all curves, the benefits of a forwarder coordination and synchronization are confirmed impressively.

6 Conclusions

Remaining Resource MAC Scheduling presented in this paper helps to improve the promising approach of interconnecting HiperLAN/2 ad hoc subnets by *Multiple-Frequency* Forwarders. In combination with coordination and synchronization of *MF*-WTs, showing benefits for two-subnet as well as for three-subnet constellations, the novel approach of forwarding in the frequency domain proves to be well applicable for H/2 multihop ad hoc environments. Future investigations will focus on Link Adaptation and compare single and multihop networks including co-channel interference.

7 Literature

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