Effects of Forwarder Coordination on the Data Transmission Across HiperLAN/2 Ad Hoc Subnets

Jörg Peetz, Bane Strahinjic
Communication Networks
Aachen University of Technology
Kopernikusstr. 16, 52074 Aachen, Germany
E-Mail: Joerg.Peetz@comnets.rwth-aachen.de

***Abstract*-The HiperLAN/2 (H/2) standard has been designed by the European Telecommunications Standards Institute (ETSI) to provide high bit rate wireless communication in the 5 GHz frequency band. Beside infrastructure based networking, one-hop ad hoc communication for centrally coordinated single subnets is covered by a profile for Home Environments. The objective of a novel Multiple-Frequency Forwarding technique, introduced in [1] and [2] for the first time, was to overcome the restrictions of the one-hop configuration and to extend it to multihop ad hoc connectivity. This forwarding concept is very flexible in use and proved to fulfill even the Quality of Service requirements of MPEG video and Constant Bit Rate traffic, see [3]. The paper discusses the advantages of forwarder coordination, it proposes technical solutions, and evaluates the performance of double and triple subnet constellations with up to 4-hop inter-subnet routes.**

I. 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, a convergence layer enables to adapt to different 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 realize forwarder coordination. 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 route length in hops and number of subnets.

II. Subnet Interconnection Based on Forwarding in the Frequency Domain

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). 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.

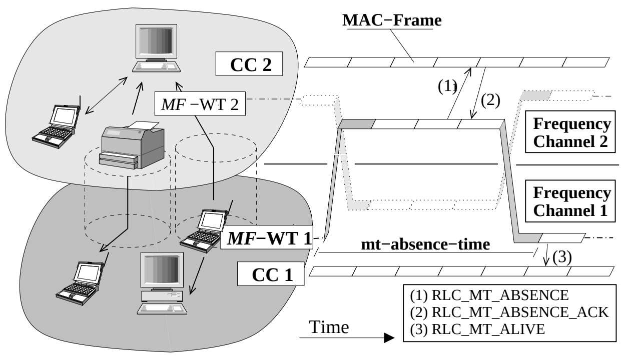

Fig. 1. Communication Across Subnets Via *MF*-WT(s)

1) Forwarding Concept: Inter-subnet data transmission 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 is started from the following MAC frame on. After switching frequency, that is assumed to last about 1 ms [9], the Broadcast Channel transmitted 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. Otherwise, it is scheduled automatically and just starts transmission. To return to subnet 2, the MT_Absence procedure is executed again. This sequence is repeated continuously.

2) Addressing in Multihop Environments: An important issue that has to be raised in this context is the question how terminals belonging to adjacent networks are addressed. Mainly, two solutions exist – first, an extension of the used terminal address, the so-called MAC-ID, valid only in one-hop networks for an additional network identification (NET-ID), and second, a signaling during forwarder establishment and association. The NET-ID is currently used in H/2 to identify networks for reasons of security management. Per subnet, it is assigned a random number that is broadcast in every MAC frame by the CC and exchanged when a new WT joins the network. To combine this 10 bit number with the MAC-ID forming an address right for multihop communication, will cause some implications on the performance as the MAC-ID is currently included in every Protocol Data Unit (PDU). Thus, a change in the data structure means higher protocol overhead. The second proposal of an enhanced signaling shows better efficiency for the data transfer because the address format does not change except for the reservation of a range of MAC-IDs for terminals in adjacent networks. However, this solution induces higher effort in signaling whenever an *MF*-WT is initiated. It is required to inform the forwarders about all terminals in a subnet and to create and update routing tables in each *MF*-WT to map the subnet specific MAC-IDs. In the case of high mobility, this concept is disadvantageous due to the increased signaling overhead. For the H/2 HE, however, most of the WTs are expected to be movable, but not mobile, resulting in slow topology changes.

III. Forwarder Coordination and Synchronization in Most Likely Multihop Scenarios

A. *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. 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 connecting *M* subnets by *N* forwarder nodes are at least theoretically possible.

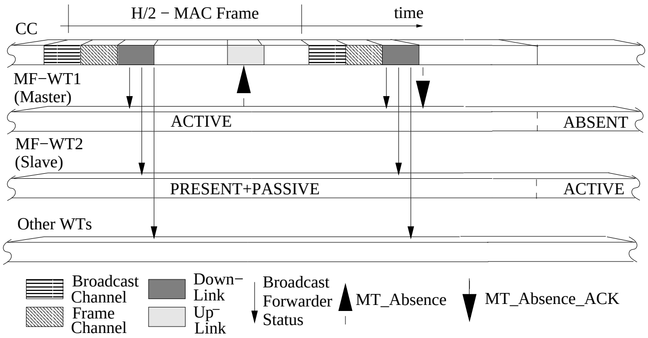

Fig. 2: Master-Slave Coordination of Forwarder Candidates

1) Master-Slave Concept: 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 RLC message "FORWARDER_STATUS_MAP" 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 or NET-ID. 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.

2) Alternating Forwarders: With such a CC controlled forwarder coordination, it is possible to link two subnets by several forwarders - asynchronous or synchronous as well. Latter is possible 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, we call it "Alternating Forwarders", a more time-continuous interconnection can be achieved resulting in substantial improvements for throughput and delay [2].

B. *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. 10, 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 III.C, a third variation is explained that can be seen as special case of the previous one, assuming three subnets with joint coverage area.

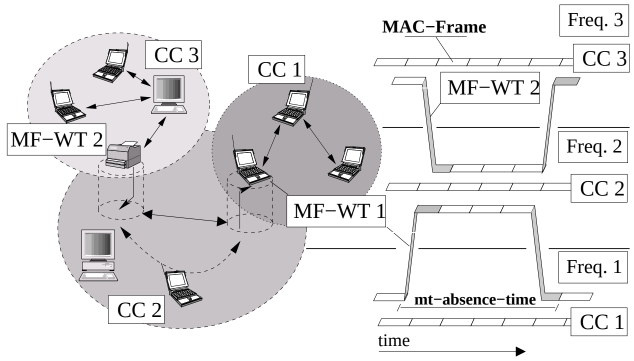

Fig. 3: Multihop Scenario of Three Subnets Adjacent in Pairs

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.

C. *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][11].

This idea could be taken over for H/2 forwarders in the frequency domain.

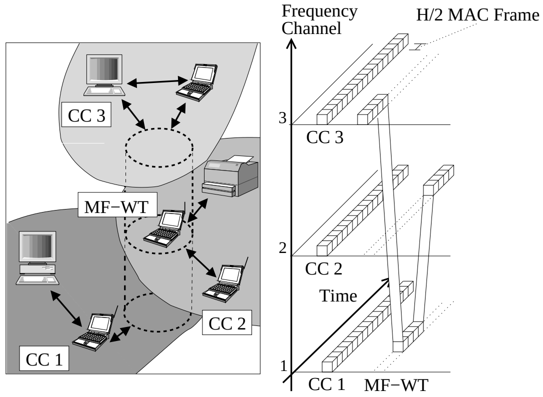

Fig. 4: Forwarder in the Frequency Domain Connecting Three Subnets

IV. PERFORMANCE EVALUATION

A. *Simulation Scenarios*

In order to evaluate multihop ad hoc communication under realistic conditions, event driven computer simulations [12] 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.

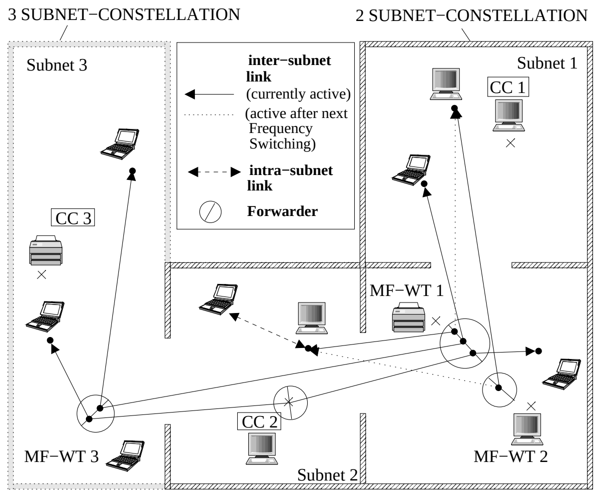

Fig. 5. Multihop Ad Hoc Simulation Scenario

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 DLC User Connections (DUC) 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.

B. *Two-Subnet Constellation – Comparison of Single MF-WT and Coordinated Alternating Forwarders*

1) *Throughput and Delay Analyses:* The performance of *inter*-subnet links forwarded by a single *MF*-WT respectively two alternating *MF*-WTs was analyzed for unidirectional as well as for bidirectional Poisson traffic. The absence periods have been chosen symmetrically in length for both subnets. In Fig. 6, maximum throughput as well as delay characteristics are plot against the absence period length (mt-absence-time) given in the unit of MAC frames (2ms). The results are founded on simulation series whereby the load is increased until throughput saturation. From the left diagram, the upper throughput limitation can be derived to be 38 Mbit/s for two alternating and 20 Mbit/s for a single *MF*-WT. The interesting fact that forwarding is not possible for absence times below three MAC frame, is caused by frequency switching, synchronization, and resource request overhead.

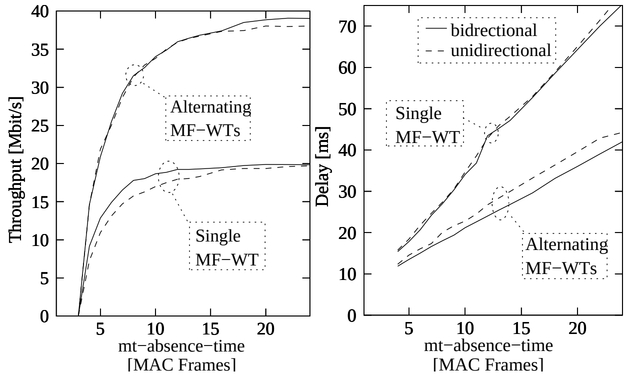

Fig. 6. Throughput and Delay versus Absence Time

In the right plot, the delay is displayed for traffic loads close to, but excluding the saturation phase. Beyond the linear relation of delay to absence time, this diagram shows that the two-forwarder approach outperforms the single *MF*-WT not only for throughput, but also for delay. A combined representation of the results is given in Fig. 8 for a bidirectional traffic load comparing throughput versus delay graphs of the single *MF*-WT with the alternating forwarders concept. This diagram includes the performance characteristic of an *intra*-subnet connection as reference and, additionally, results for three-subnet formations that will be illustrated in section IV.C in more detail.

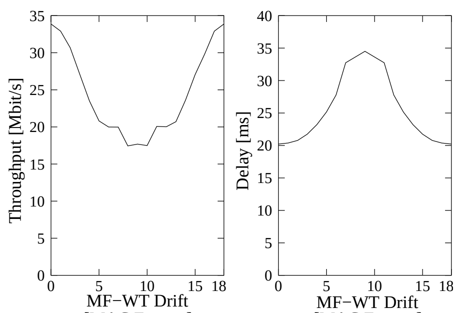

Fig. 7: Influences of Forwarder Drift on Throughput and Delay

From Fig. 7, some insight can be gained into how the performance is affected by a loss of synchronization in the case of two alternating forwarders connecting two subnets. With an absence time setting of 10 MAC frames, both forwarders become synchronous again for a drift of 18 MAC frames explaining the periodicity of throughput and delay characteristics. It is well recognizable that if two forwarders operate in the same subnet for matching time periods, at least the performance of a single forwarder can be achieved – the corresponding drift equals 9 MAC frames in the scenario investigated. This positive effect is mainly caused by the master-slave coordination of both *MF*-WTs, see section III.A.

C. *Configuration of Three Subnets Adjacent in Pairs*

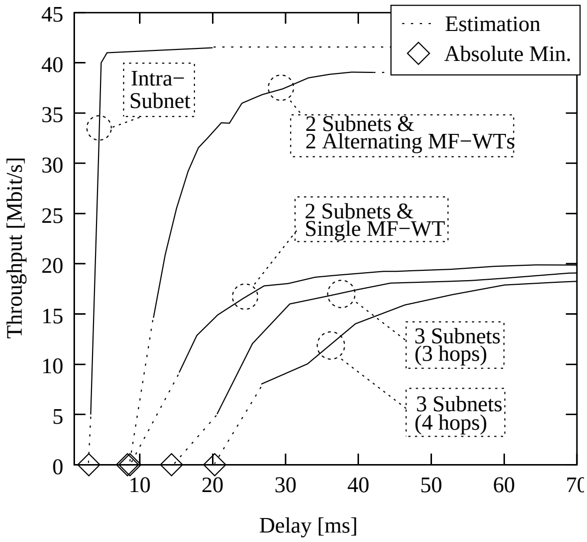

Fig. 8: Performance of Multihop Traffic

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. 8 the performance characteristics of those 3- to 4-hop connections are depicted in the form of throughput vs. delay curves. It turns out that especially the delay is affected by an additional hop via the CC.

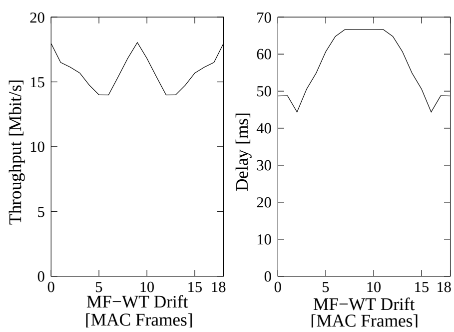

Fig. 9: Asynchronous Forwarder Operation in a Three-Subnet Scenario

The examination of drifting single MF-WTs in a three-subnet scenario assumes conditions comparable to those for the two-subnet constellation. For example, the absence time was chosen to be equivalent at 10 MAC frames. Again, the periodicity of throughput and delay graphs manifests. 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.

D. *Summary and Discussion of Simulation Results*

In order to resume the investigations, Fig. 10 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 optimized value of 5 MAC frames, a throughput optimized value of 15 frames and 10 frames in between.

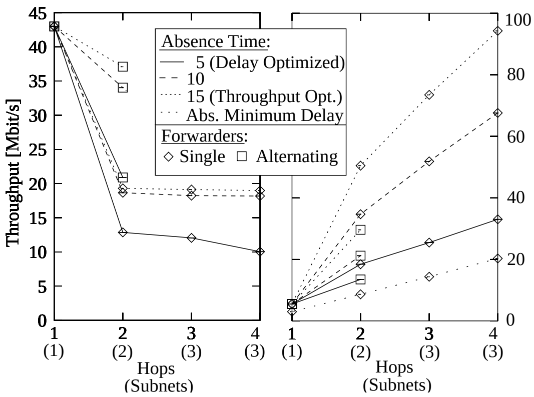

Fig. 10: Throughput & Delay vs. Route Length (Hops) & Subnets

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.

V. CONCLUSIONS AND OUTLOOK

This paper gives an overview of multihop communication in HiperLAN/2 ad hoc networks. Different network topologies are discussed and solutions specifically adapted for two- as well as for three-subnet configurations have been presented. By simulations, the performance characteristics were investigated whereby both single and alternating forwarders approach and 2- up to 4-hop communication have been evaluated. In all cases, the coordination and synchronization of forwarders proved to have positive effects on the performance of data transmission across H/2 subnets. Future research will focus on further subnet formations, routing aspects, and the influences of co-channel interferences.

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