A Centralized Routing Scheme Supporting Ad Hoc Networking in Dual Mode HIPERLAN/2

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ABSTRACT

The IST project BroadWay introduces ad hoc functionality at 60 GHz in the traditional 5 GHz HIPERLAN/2. The dual mode of operation primarily aims at offloading the 5 GHz cell of HIPERLAN/2 in very dense urban deployments. The peculiarities of the BroadWay system make the development of a routing scheme a challenging task. This paper explores the routing perspectives of the BroadWay system and describes the *centralized routing scheme* for the dual mode HIPERLAN/2. *Neighborhood discovery* and *route selection* are the basic components of the centralized routing scheme, where the Access Point (AP) is responsible for allocating the resources and establishing the routes at both 5 and 60 GHz. BroadWay introduces modifications to the MAC of HIPERLAN/2 regarding new messages and framing considerations at both frequency bands in order to allow for the new routing functionalities.

I. INTRODUCTION

BroadWay is a hybrid dual frequency system based on a tight integration of HIPERLAN/2 OFDM efficient technology at 5 GHz and an innovative fully ad hoc extension of it at 60 GHz, named HIPERSPOT. The main objective of BroadWay is to extend existing broadband wireless LAN systems by offloading very dense urban deployments and delivering higher data rates (up to 500Mbps per user). BroadWay incorporates the ad hoc functionality into the centralized architecture of HIPERLAN/2, supporting sufficient terminal mobility while providing much higher capacity and increased privacy [1][2].

Ad hoc networking is considered for various reasons such as when there is no infrastructure (mostly in disasters, emergency cases or military operations), or in order to extend the coverage area of a WLAN. The innovation of BroadWay is the proposal for a system that takes advantage of ad hoc networking at 60 GHz inside the existing HIPERLAN/2 infrastructure. This dual mode of operation and the hybrid technology of BroadWay require the development of a different routing scheme than those in the cellular architecture of HIPERLAN/2 or in completely infrastructureless ad hoc networks.

In HIPERLAN/2, the AP is responsible for allocating the needed resources for the communication between two Mobile Terminals (MTs) [3][4]. Every established path consists of two hops: one between the source node and the AP and another from the AP to the destination node. The AP always receives the data sent by any MT inside its cell no matter whether the AP is the destination or not. The Quality of Service is guaranteed due to the connection-oriented nature and the TDMA structure of HIPERLAN/2 [5]. To extend the HIPERLAN/2 DLC basic standard designed for a cellular infrastructure, the Home Environment Extension (HEE) of HIPERLAN/2 provides for an ad hoc functionality that allows for a plug-and-play type of operation [6]. In the current HEE specification, a one-hop ad hoc connectivity is provided if all MTs are within the transmission range and one MT assumes the role of the Central Controller. In order to add multi-hop networking functionality to HIPERLAN/2, forwarding techniques – operating mainly in the frequency domain – have been proposed [7][8].

In pure ad hoc networks, all MTs participate as peers in multi-hop route establishment. Many ad hoc routing protocols have been proposed in the literature [9][10][11]. Proactive protocols maintain routes to all destinations by exchanging their routing tables periodically; they result in minimal initial delay but face high probability of stale information and higher overhead. Reactive protocols create paths only when needed. Although they have the advantage of low overhead, they face higher delay and they are less effective under high load. Hybrid protocols try to blend the advantages of both proactive and reactive schemes; this way, the routing protocols can achieve better performance in topologies with increased node mobility, a large number of nodes and a large network span. Furthermore, several routing protocols have been proposed addressing critical issues such as energy efficiency [12][13] and QoS support [14][15][16].

BroadWay is based on the HIPERLAN/2 architecture and aims at proposing enhanced techniques in order to incorporate the ad hoc functionality at 60 GHz. Consequently, routing in BroadWay is a complicated and challenging task. The cellular architecture and ad hoc techniques have to be properly combined to provide for an efficient routing scheme for the BroadWay system.

The remainder of the paper is organized as follows. In Section II, the network's dual mode of operation is presented. Section III describes the proposed centralized routing scheme highlighting the impact of neighborhood discovery on the resulting system's performance and the metrics considered by the route selection process. Finally, the research challenges are summarized and future work is delineated in Section IV.

II. DUAL MODE OF OPERATION

A HIPERLAN/2 cell contains the AP and the MTs. BroadWay introduces two modes of operation: the cellular one at 5 GHz and the ad hoc mode at 60 GHz. At any time instant, one 5 GHz and several 60 GHz channels (based on the channel bandwidth and spacing) can be used inside the cell. The AP operates at 5 GHz and at 60 GHz simultaneously, whereas the MTs can only operate at one frequency band at a time – meaning that they must switch from one mode of operation to the other. One of the critical issues of BroadWay is the switching time required not only for changing band (5/60 GHz) but also for switching between the various 60 GHz channels. In any case, the induced delay by the Radio Frequency components will be of the order of a few hundreds of microseconds; the maximum delay specified in the HIPERLAN/2 standard is 1ms [17].

HIPERSPOT supports two compatible classes of MTs: class A and B. Class A is a lower cost device and has the same transmission capabilities as one HIPERLAN/2 logical channel. Class B, associated with high-end devices, provides for significantly higher data rates (> 100 Mbps) than those in HIPERLAN/2, by exploiting the larger bandwidth available at 60 GHz.

The physical characteristics of the 60 GHz channels [18] (short communication distances that do not exceed 15-20 meters, and Line Of Sight constraints) combined with the expected effects of users' and environment's mobility result in the establishment of short-lived 60 GHz paths that are difficult to consist of more than 2-3 hops.

An important objective associated with the centralized architecture in the BroadWay system is to keep the 5 GHz band as the primary one and the AP as the coordinator of every communication (5/60 GHz) inside the HIPERLAN/2 cell. Furthermore, the proposed architecture should cater to the HIPERLAN/2 standard.

A. Operation at 5 GHz

The AP generates frames as standardized in HIPERLAN/2 (modified to include the enhanced functionalities of BroadWay) and is responsible for allocating the resources associated with both frequency bands.

Every MT that is inside the AP's cell is associated with the AP. MTs operate at 5 GHz most of the time (unless they can hear the transmissions of the AP at 60 GHz or participate in an established 60 GHz path). Connections at 5 GHz are established as described in the standard [3][5].

B. Operation at 60 GHz

The AP operates simultaneously at a predefined 60 GHz channel (it does not switch between 60 GHz frequency channels), generating frames as in the 5 GHz band. The coverage area of the AP at 60 GHz is only a part of that of the 5 GHz cell. The 60 GHz AP is responsible for the MTs that belong to its coverage area and are tuned to its 60 GHz channel.

MTs are tuned to the predefined 60 GHz channel only after they have discovered that they belong to the 60 GHz cell of the AP (neighborhood discovery, see Section III) or have been informed by the AP to participate in an established 60 GHz path. The routing architecture at 60 GHz employs *clusterheads* and *forwarder nodes.* A clusterhead is a MT that generates frames at 60 GHz and controls the communication resources in its coverage area (cluster); the role of a clusterhead in BroadWay is limited to routing data since the resource allocation is mainly the AP's responsibility. A forwarder node is the MT that can hear the transmissions of more than one clusterheads and is capable of switching between different 60 GHz frequency channels to enable intra-cluster communication (multi-hop communication). Both clusterheads and forwarder nodes are equipped with extra functionalities to support the establishment of the 60 GHz paths. All other MTs are *ordinary nodes*.

The AP at 60 GHz can be considered as a clusterhead that never switches back to 5 GHz.

III. CENTRALIZED ROUTING SCHEME

To support routing in the BroadWay system the following are necessary: to determine which nodes operate at which frequency band as well as to establish efficient routes at 60 GHz.

According to the centralized routing scheme, every MT starts operating at 5 GHz upon switching on and gets associated to the corresponding AP of HIPERLAN/2 [3]. Periodically or on an event-driven basis, the AP (both at 5 GHz and at 60 GHz) broadcasts a message to initiate the neighborhood discovery process. This process provides the AP with 60 GHz topology information (every MT's one-hop away neighborhood and the quality of the corresponding links when operating at 60 GHz). The AP is responsible for establishing the paths at both frequency bands and allocating the needed resources, the so-called route selection.

A. Neighborhood Discovery

Neighborhood discovery consists of 3 phases and aims at determining the directly reachable neighbors of a node at 60 GHz (the nodes that are one hop away). Every node should participate in the neighborhood discovery process. Each node then maintains neighborhood information in the form of a list containing the neighbors and the status of the corresponding links. This information is sent to the AP, which is responsible for the route selection.

In *phase 1* (see Figure 1), the AP decides on performing neighborhood discovery. This decision could be taken periodically or be event-driven (based on several criteria such as the available bandwidth at 5 GHz, the density of users inside the 5 GHz cell, the number of new users in the system, the detected link breakages at 60 GHz and time elapsed since the last neighborhood discovery). Then, the AP informs all MTs inside its coverage area (both at 5 GHz and at 60 GHz) indicating the 60 GHz frequency channel that should be used for neighborhood discovery and the time instant at which this procedure should be initiated. This broadcast information is included in the *neighborhood discovery message*. The frequency channel used for the neighborhood discovery is the same as that used by the AP at 60 GHz. However, the MTs may be assigned a different frequency channel when constructing a communication path at 60 GHz; thus, the link state information obtained during the neighborhood discovery process may not be as accurate since interference levels and link states depend on the particular frequency channel. The acquisition of more accurate information about the topology at 60 GHz would require more time spent for discovering the neighbors at the specified frequency channel first, and then evaluating the link states associated with the assigned channel. Consequently, it is assumed that the information obtained by this process is sufficiently accurate and can be used by the AP when taking routing decisions.

In *phase 2*, the MTs exchange *hello messages*, containing their MAC IDs, in order to discover their one-hop away neighbors and construct their *link state tables*. The AP also sends a hello message indicating its presence at 60 GHz; this way, MTs can determine whether they belong to the 60 GHz cell of the AP. After receiving its neighbors' hello messages, a MT can determine the state of each link with its one-hop away neighbors (by using physical layer information such as Signal-to-Noise-Ratio and interference levels). All MTs can then construct their own link state tables, which consist of their neighbors and the corresponding link states.

In *phase 3*, the MTs forward the collected information to the AP, which is responsible for making the routing decisions in both frequency bands. Besides its link state table, every MT could send an indicator of its remaining battery lifetime, so that energy consumption aspects can be taken into account as well.

The most critical parameters of the neighborhood discovery process that impact on the efficiency of the resulting system are its duration and frequency of occurrence. The first one depends on the switching time and the bulk of the transmitted information, while the latter is closely related to the longevity of the validity of the collected information.

The duration of neighborhood discovery (T_{nd}) can be calculated by the sum of the duration of phase 2 (T_2) and phase 3 (T_3). Phase 1 involves the broadcast information provided by the AP and is not considered to contribute to the neighborhood discovery duration.

In order to calculate T_2, we consider a HIPERLAN/2 cell, where a MAC ID-based algorithm is applied. According to the MAC ID-based algorithm, every MT sends its hello message at the time instant defined by its MAC ID (that is assigned by the AP). The AP can send its hello message after all MTs' transmissions are completed. Thus, the time needed for the exchange of hello messages cannot exceed T_2 (this is an upper bound on the duration of phase 2 in order to avoid collisions):

$$T_2 = t_s + \max(\text{MAC IDi}) * t_{hello} + t_{hello\text{-}AP} \qquad (1),$$

where:

t_s: switching time between 5 GHz and 60 GHz frequency channel for neighborhood discovery

max (MAC IDi): maximum assigned MAC ID value

t_{hello}: time needed for a MT to transmit a hello message

$t_{hello\text{-}AP}$: time needed for the AP to transmit a hello message

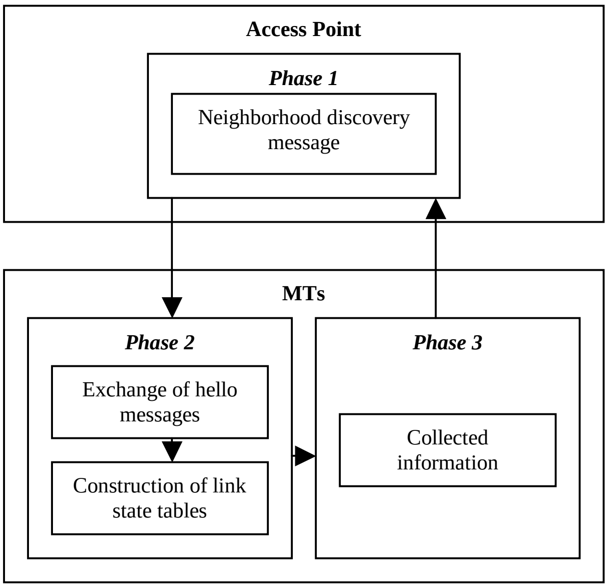

Figure 1: The Neighborhood Discovery Process

If MTs are properly coordinated by the AP and send their collected information to the AP in consecutive time intervals, then T_3 will be given by:

$$T_3 = t_s + \Sigma_n (t_{link\text{-}state\ table})_i \qquad (2),$$

where:

t_s: switching time between the 60 GHz frequency channel of the neighborhood discovery and the frequency channel of operation (5 GHz or 60 GHz)

n: number of users/MTs in HIPERLAN/2 cell

$(t_{link\text{-}state\ table})_i$: time needed for MT i to send its link state table to the AP

The duration of neighborhood discovery is:

$$T_{nd} = T_2 + T_3 \qquad (3)$$

Among the parameters that affect the duration of neighborhood discovery, the exchange of hello messages obviously wastes negligible time compared to the transmission of the link state tables. Furthermore, the switching time between the two frequencies is larger than the hello messages' exchange duration. For example in a HIPERLAN/2 cell with 200 users – using the message formats and the transmission speed of the standard – less than 1 msec is needed. Consequently, the effort to reduce the overall duration, and thus increase the efficiency of neighborhood discovery in the centralized routing scheme, is focused on the scheduling of the transmissions of the link state tables to the AP. It should also be noted that link state tables could include only the information referring to the changes in the 60 GHz neighborhood that occurred between two consecutive neighborhood discovery processes.

Due to the fact that 60 GHz links are highly unstable and short-lived, the neighborhood discovery process should be relatively frequent to provide the AP with valid and credible information. Since the 60 GHz links may typically last for only a few seconds, the information collected by the neighborhood discovery process needs to be refreshed frequently – every 1-3 seconds for example. This would require an additional overhead that would not exceed 0.2-2% (3-10 MAC frames out of 500-1500 MAC frames).

B. Route Selection

Under the centralized routing scheme in the BroadWay system, the AP is fully responsible for managing the collected information, deciding on the path between the source and the destination node and informing the participants in the route about the characteristics of the established connection and rules for their participation in it. The AP has the "leading" role in making decisions for paths not only at 5 GHz (traditional HIPERLAN/2) but also at 60 GHz. Consequently, the ad hoc nature of routing in the resulting system is limited, since the MTs do not participate in routing packets hop by hop from the source to the destination based on their own information, but they only collect the essential link state information for the 60 GHz topology on behalf of the AP. This means that MTs only forward data but never decide on their own.

The centralized routing scheme considers the metrics on which a routing decision is based and assigns routing roles to the participants of a constructed 60 GHz route. Every MT (source, intermediate, destination node) is equipped with the functionality of a cluster head or a forwarder node at 60 GHz (as described in Section II). The AP makes the selection of a path among potentially several candidate paths that provide connectivity between the source and the destination. This decision should be based on the following criteria:

1. Bandwidth: Since offloading the 5 GHz band is the primary objective of BroadWay, the available bandwidth at 5 GHz is one of the most important quantities that the AP has to consider. The connections at 5 GHz are more reliable (less probable link failures), but at the same time 60 GHz links can offer higher rates.

2. Number of hops: In the traditional HIPERLAN/2, the AP forwards packets using the 5 GHz band on behalf of the source node. In the BroadWay system, packets can be forwarded by MTs at 60 GHz without necessarily the participation – as an intermediate node – of the AP. The ad hoc functionality of the resulting system includes the possibility of constructing multi-hop paths between the source node and the destination node. The number of hops constituting the 60 GHz paths affects the probability of the route's failure. Every added hop in a multi-hop path increases the probability of a route failure (at least one participating link fails). Since a constructed route that consists of a large number of hops is more likely to fail – and consequently the system's throughput is reduced – the probability that the AP will select paths with more than 2-3 hops is low. Specifically, the AP can decide for multi-hop paths of any number of hops, but the weight/value of the associated decision metric will limit the probability of choosing such routes.

3. Link State: When the AP decides on a route, the states of the one-hop links of the candidate path at 60 GHz will be considered as well. This kind of information is collected during the neighborhood discovery process and is "translated" into routing information. 60 GHz paths, which consist of links with "better" characteristics, will be preferred against others. Some routes with a larger number of better quality links can be more reliable than others with a smaller number of worse quality links.

4. Battery Lifetime: This information is sent during the forwarding of link state tables to the AP from each MT. MTs with longer remaining battery lifetime lead to more stable and longer-lived routes.

5. On-going traffic: Eventually, there could be MTs that participate in several 60 GHz paths. The AP should try to engage or avoid such nodes in additional paths depending on their available capacity and routing role (cluster head, forwarder node, ordinary node).

6. "History" of the request: When a request is sent to the AP for allocating the appropriate resources, there are two possibilities: either this request refers to a new connection between a source and a destination node or it refers to an older connection that faced a link failure – considering mainly the 60 GHz band – and was not completed. In the first case, the AP selects a new path based on all the other criteria/rules. In the second case, there are two alternatives: one is to construct a 60 GHz path, which does not include the failed link; the second alternative is to use the more stable 5 GHz path.

Furthermore, a route decision should depend on the time elapsed since the most recent neighborhood discovery process. The less the time elapsed since the previous collection of information the more accurate a route decision is expected to be (since link state information at 60 GHz is more probable to become stale as time passes).

7. QoS requirements: The TDMA structure (slot allocation) and the connection-oriented nature of HIPERLAN/2 enable QoS support. The route selection by the AP should meet the application’s QoS requirements in terms of required bandwidth, induced delay, etc.

8. Mobility: The AP can identify the MTs that introduce more topological changes (higher probability of link failures because of invalid/stale link information), by considering the 60 GHz topology updates (neighborhood discovery). The AP can record the MTs that participate in the link failures and use this information to estimate a mobility level metric for every MT inside the cell of 5 GHz. The purpose of this metric is to try to minimize the probability of using stale information.

IV. CONCLUSIONS

Routing in the BroadWay system includes innovative mechanisms since it combines ad hoc techniques and a cellular architecture. In the centralized routing scheme, the AP is responsible for making routing decisions and establishing the required paths choosing between the 5 GHz and 60 GHz band. The neighborhood discovery process provides the information needed for the 60 GHz operation. Due to the physical characteristics of the 60 GHz band (LOS constraints, short transmission ranges), the users’ and environment’s mobility and the existing infrastructure, a dual mode of operation is designed with the 5 GHz band being the primary frequency band whereas 60 GHz channels provide for offloading the 5 GHz band and supporting higher rate applications. Thus, BroadWay will cater to HIPERLAN/2 requirements and support HIPERSPOT environments at the same time.

V. ACKNOWLEDGMENT

The BroadWay project (IST-2001-32686) is partly funded by the Commission of the European Community.

The partners involved in the project are the Motorola Labs France, TNO-FEL Netherlands, Intracom and the National & Kapodistrian University of Athens, Greece, IMST, IRK and Dresden University of Technology, Germany and FARRAN, Ireland.

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