INCREASING CAPACITY IN DUAL-BAND WLANS THROUGH AD-HOC NETWORKING

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Abstract - The ad-hoc networking paradigm – originally conceived to cope with infrastructureless military and emergency situations – is also being considered to support the ever-evolving user requirements for higher data rates and enhance the capabilities of traditional networks. The Centralized Ad-Hoc Network Architecture (CANA) proposed in this article aims at increasing substantially the capacity of traditional Wireless Local Area Networks (WLANs). It is based on a dual frequency system in which the operation in the original WLAN frequency supports the centralization of some of the traditionally distributed and problematic ad-hoc functionalities enabled at the new frequency; higher-rate, shorter-range, peer-to-peer and multi-hop transmissions are possible at the new frequency, resulting in a significant increase of the WLAN capacity. In order to take advantage of the extra capacity, modifications are defined and described by exploring the HiperLAN/2 standard. The gain of the induced dual mode of operation depends on several parameters that define the performance of CANA. This article explores the performance issues that CANA arises by providing both analytical and simulation results. The overhead of CANA is rather low if one takes into account the profits of such architecture.

Keywords - Ad-hoc, HiperLAN/2, Multi-hop, Offloading, WLAN, WPAN.

I. INTRODUCTION

Telecommunications infrastructure will be a key ingredient of the future society in which information exchanges will be needed to support most of the daily life activities [1]. With the increased demand for new services based on video or data, the concept of a private area network has emerged, introducing new requirements for wireless high data rate systems. Through Wireless Personal Area Networks (WPANs), users will interface with household devices; through Wireless Local Area Networks (WLANs), users will interface with other computer users and the Internet; through ad-hoc networks, users will retain their communication when there is no infrastructure.

To accommodate the aforementioned needs, it is believed that new bands – offering a larger amount of available spectrum – need to be explored and new systems be developed that will provide for a smooth and transparent evolution from current technologies and standards. For this reason, as well as in order to efficiently support widely heterogeneous user needs and environments, it is expected that costly multi-mode terminals will be needed in the future. Composite radio systems will be required to support multi-mode terminals in a wireless environment.

In this article, a system architecture is described for a composite radio system designed to operate in both a traditional band as well as a new wider one, to enable terminal access to a higher capacity needed in high-density areas (hotspots). The proposed Centralized Ad-hoc Network Architecture (CANA) determines the rules for a scalable network architecture that is based on current 5 GHz WLAN technologies equipped with extensions in the 60 GHz frequency band (shorter-range communication) and can be seen beyond 3G scenarios.

CANA provides a hybrid dual frequency system to offload the 5 GHz band in high-density areas (in terms of users and data traffic) taking advantage of the ad-hoc networking paradigm. Ad-hoc networks require no infrastructure and have been mostly used to enable wireless communications in battlefields and emergency cases; the performance of ad-hoc networks is highly dependent on the wireless environment, mobility, topology characteristics and applications [2]. The central control that can be exercised by the 5 GHz WLAN infrastructure assumed to be present in CANA (e.g. in facilitating routing) substantially reduces the inherent weaknesses of infrastructureless ad-hoc networking while enabling, at the same time, higher access rates within the WLAN cell.

An evaluation process reveals the benefit of employing CANA under certain conditions. It is shown that CANA is beneficial in hotspot areas and in cases large amounts of data need to be exchanged among users. Simulation results support the claims of the aforementioned analysis and show that although the established short-range paths at 60 GHz may be short-living, they can be proven efficient under the proper management of CANA since the achieved bit rates are high. CANA provides for the incorporation of the ad-hoc networking paradigm in the new frequency at low overhead.

The rest of the article is organized as follows. Section II describes recent work in this area. The proposed architecture, CANA, is presented in Section III. In Section IV, the modifications needed in order to apply CANA in HiperLAN/2 (HL/2) are defined. Section V presents an evaluation process regarding the specified performance metrics. Simulation results target at shedding more light into the performance issues of CANA and are shown in Section VI. The article is concluded in Section VII.

II. AD-HOC NETWORKING IN WLANS

The growth of public WLANs is expected to be very high over the next few years [3]. Companies are deploying visitor-friendly WLANs in hotspots where people congregate, such as airports, convention centers, hotels and marinas throughout the world. It will not be long before we expect to have WLAN access just about everywhere we go.

The ad-hoc networking paradigm was first adopted by cellular networks to extend their coverage area or fill the "communication gaps" between cells [2]. Recently, it has been considered as a means for providing higher throughput inside a cell, as well. In [4], the impact of using peer-to-peer communication in a cellular wireless packet data environment is studied. Benefits in terms of spatial reuse characteristics are shown while, at the same time, several approaches are described to overcome the degradation of the overall throughput due to the inefficiencies of the ad-hoc protocols (that are typically distributed in nature) when applied in cellular networks and the greater impact in shorter-range communications. In [5], the Multi-hop Cellular Network is presented. The throughput of the new architecture is derived based on the RTS/CTS access method of IEEE 802.11 and it is shown that as the transmission range decreases the throughput of the proposed architecture increases. In [6], the peer-to-peer paradigm is employed only outside a circular area around the Access Point (AP) and the cellular paradigm inside this circular area. This approach is proposed to allow for a coordinated and high-throughput one-hop access to the AP of the Mobile Terminals (MTs) within this (small) high-traffic circular area by avoiding the detrimental impact of multi-hop interference. A hybrid wireless network architecture is described in [7] that is based on a cellular infrastructure but operates in either the ad-hoc mode or the cellular mode depending on the performance of each mode for the state of the network at any given time. The base station – or the AP – of the cellular infrastructure decides on the mode of operation. In [8], an architecture is proposed based on multiple data channels operating at different power levels. This way, spatial reuse is enhanced, without substantially increasing the number of hops. The hierarchical cellular multi-hop network is described in [9]. By introducing fixed multi-hop capable nodes, the coverage increases while the capacity potentially grows and the power consumption decreases.

In order to incorporate the ad-hoc networking paradigm into a WLAN and form a multi-hop cellular network, the transmission power of the MTs is typically reduced. Due to spatial reuse, the nominal capacity can be shown to increase [5]; this higher capacity can actually be useable only under certain traffic conditions. When traffic is destined to the backbone Internet, the destination within the wireless cell is the AP, and the channel around the AP becomes a bottleneck, limiting the throughput performance of the peer-to-peer network model to even below that of the cellular network model [6]. Moreover, the throughput of a multi-hop cellular network is compromised by the vulnerability of multi-hop routes due to topology changes caused mainly by mobility (link failures) [4]. Even under low mobility conditions, the shorter-range paths induced by the ad-hoc networking paradigm are short-living and frequent route discoveries are required to maintain paths wasting, at the same time, a significant part of the available bandwidth. The overhead caused by such route discoveries may be reduced significantly if an AP covers the entire region and undertakes the route discovery task in a centralized manner. In this case, a multi-radio environment should be considered supporting two modes of operation (ad-hoc and cellular mode) enabled by multiple radio interfaces; one radio frequency may be used for communication with the AP (control channel) to support the establishment of multi-hop paths in the other frequency (one or more data channels) [7], [8]. Thus, control messages can be sent over a single hop to the AP ensuring that a MT can communicate with the AP without the need for any route discovery process, while the use of several data channels can increase capacity.

The proposed architecture, CANA, provides for a dual mode WLAN. The ad-hoc networking paradigm is applied at a new frequency yielding high transmission rate paths, which – despite their potentially low lifetime – can significantly offload the traditional WLAN frequency. The latter is used to set up such multi-hop paths, as well as for single-hop data transmissions to/from the AP. The study is limited within a cell, highlighting the ad-hoc networking challenges in the new environment due to the dual mode of operation and the fact that the MTs are equipped with only one Radio Frequency Front End (RFFE), and, thus, have to switch between the two frequency bands [10].

III. THE PROPOSED ARCHITECTURE: CANA

A. Motivation

CANA is suitable for hotspots including private (e-home entertainment, business) and public (fast outdoor downloading) applications. It is designed to cope with very dense user environments without sacrificing the user expectations in terms of throughput. The primary objective of CANA is to establish a bridge between the 5 GHz band and the unlicensed radio spectrum in the 59-65 GHz range by conceiving a dual frequency WLAN that will provide for a smooth evolution to the 60 GHz from the existing 5 GHz technology, with backward compatibility and increased total system capacity.

In this article, we describe a new system and the necessary modifications of the WLAN architecture focusing mainly on the layers above the physical layer. The basic WLAN architecture employed is HL/2 [11], to which ad-hoc functionality is added in the 60 GHz frequency band. The basic functionalities of the proposed architecture (CANA) can be applied to the IEEE 802.11 WLAN as well. CANA may be viewed as a first step toward a new platform that would provide for an integrated WLAN/WPAN technology capable of meeting user expectations in terms of throughput and sophisticated applications. The evaluation process as well as simulation results present the benefits of the proposed architecture and highlight the performance issues arisen by its establishment.

CANA is presented here as an extension of HL/2 because of the good characteristics of the Medium Access Control (MAC) layer of the latter (TDMA structure), which facilitates the scheduling of resources (data and control messages) and the provision of diverse quality of service inside the cell. Although HL/2 has not become a commercial product and is not expected to gain a share in the WLAN market (where IEEE 802.11 dominates), a lot of standardization effort targeting high data rate WLANs/WPANs is based on its features. For example, the IEEE 802.11 High Throughput Study Group (HTSG) is a new study group, chartered to define the requirements for a high-throughput future WLAN standard by modifying the current WLAN architecture. The currently under specification IEEE 802.15.3 MAC has a lot of commonalities with the HL/2 Home Extension [12]. In Japan, the Multimedia Mobile Access Communication Systems Promotion Council (MMAC) has recently demonstrated a system that enables a high-speed wireless access network (HiSWAN), which is compatible with HL/2, standardized by the Association of Radio Industries and Businesses (ARIB) [13].

The propagation properties at 60 GHz and previous research results and experiments, [14], suggest that the 59-65 GHz band is well suited for CANA: i) a large chunk of spectrum is available enabling a very large system capacity and ii) the short-range operation facilitates privacy and allows for aggressive frequency reuse. The IEEE 802.15.3, which deals with high data rate WPANs, could be a good forum for addressing future 60 GHz standardization.

B. Dual Mode of Operation

CANA consists of a hybrid dual frequency system based on a tight integration of HL/2 and a fully ad-hoc extension of it at 60 GHz. Thus, one main peculiarity in CANA is the existence of two separate frequency bands. This situation differs from frequency division multiplexing – where frequencies belonging to the same band are utilized – since the two bands are characterized by entirely different propagation characteristics and resource (bandwidth) availability, as well as require different hardware implementations to support them. This "gap" between the two bands becomes evident during the operation of the system since each MT operates at only one band at each time instant; due to cost constraints, each MT is equipped with only one RFFE. Consequently, two network topologies are defined: the 5 GHz and the 60 GHz.

The AP is equipped with two RFFEs and is always active in both network topologies with a different coverage area for each band, resulting in – virtually – two APs: the 5 GHz AP and the 60 GHz AP. Due to the different propagation properties in the two bands (as mentioned earlier), the coverage area of the 60 GHz AP is significantly smaller than that of the 5 GHz AP (approximately 10m versus 50m for indoor applications [15]). Consequently, in order for MTs to reach the 60 GHz AP when outside its small coverage area, a multi-hop path needs to be established. CANA allows for the efficient establishment of multi-hop routes inside a cell.

1) Operation at 5 GHz: The 5 GHz AP generates TDMA frames with duration of 2ms and forwards data on behalf of the MTs to the corresponding destination as standardized in HL/2 [11]. Moreover, it is responsible for allocating the resources associated with *both* frequency bands. Every MT that is inside the 5 GHz AP's cell is associated with it. MTs tune at 5 GHz at first (association with the 5 GHz AP) and operate at 5 GHz most of the time, unless they participate in an established 60 GHz path. Association with and connections at 5 GHz are established as described in the HL/2 standard [11].

2) Operation at 60 GHz: A similar TDMA structure as in HL/2 is applied to assure compatibility; the frames at 60 GHz have the same length as those in HL/2 (2ms). Depending on the applied modulation scheme, the constellation size and the cost of the MT, the transmission rates can reach 100-700 Mbps [16]. Several frequency channels may be used within the 60 GHz band.

The 60 GHz AP operates at a predefined 60 GHz channel, generating frames as in the 5 GHz band; it does not switch between 60 GHz frequency channels. The 60 GHz AP is responsible for the MTs that belong to its coverage area and are tuned to its 60 GHz channel. It stops generating frames at 60 GHz only during the *Neighborhood Discovery* (ND) process – as explained later. MTs can operate in any of the available 60 GHz channels, which can be different at different times. They may be tuned to any of the available 60 GHz channels if asked by the 5 GHz AP, to participate in an established 60 GHz path or the ND process.

CANA defines three different roles for the MTs that operate at 60 GHz (described below) that are all assigned by the 5 GHz AP. This distinction is based on the different functionalities that a role encompasses and not on different hardware capabilities. Each MT maintains its assigned role for as long as it is dictated by the 5 GHz AP or until an established path it participates in breaks. An MT can undertake only one role at a time but this role may change over time as needed.

1) Clusterhead (CH): A CH is a MT that generates frames at 60 GHz and controls the communication resources for the MTs in its coverage area (cluster), that is, hear its transmissions. The role of a CH in CANA is primarily routing data, since the resource allocation is mainly the 5 GHz AP's responsibility. The CH assumes a resource allocation responsibility only to control one- and two-hop communication inside its cluster (intracluster communication), taking in this case some of the traffic management burden from the 5 GHz AP. The 60 GHz AP can be considered as a CH that never switches back to 5 GHz.
2) Forwarder Node (FN): Adjacent clusters operate at different 60 GHz frequency channels to avoid interference. A FN is a MT that can hear the transmissions of more than one CHs and switches between different 60 GHz frequency channels to enable intercluster communication (more than two hops).
3) Common Node (CN): All other MTs are CNs. A CN is considered to be part of a cluster if it hears the frame of the associated CH.

Figure 1 depicts a time instant of CANA showing the different roles of a MT at 60 GHz.

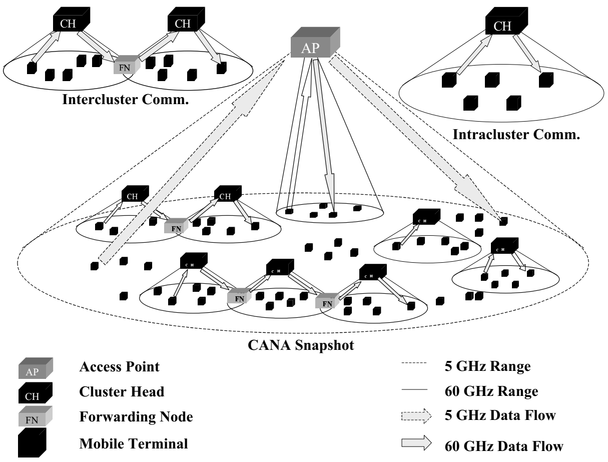

Fig. 1. A time instant of CANA

C. Routing in CANA

Routing in CANA is designed to effectively combine the ad-hoc networking paradigm at 60 GHz and the cellular networking paradigm at 5 GHz.

Routing at 5 GHz is rather straightforward and is as defined by HL/2 [11]. The 5 GHz AP has the primary role in scheduling the transmissions in the network, allocating the resources inside its coverage area and forwarding data on behalf of the MTs. Mobility (within the coverage area of the 5GHz AP) does not have any impact on routing decisions and connectivity with the 5 GHz AP is considered to be guaranteed for all MTs. Nevertheless, resource availability at 5 GHz is a major issue as the number of users increases and becomes necessary to offload the traffic at 5 GHz.

At 60 GHz, the communication range does not exceed 15 meters at most, [16], depending mainly on the constellation size that also determines the transmission speed; higher transmission rates are achieved over a shorter communication range. At the same time, user and environment mobility make the already vulnerable 60 GHz links unstable, further increasing the probability of data losses in the constructed paths. CANA exploits the presence of the 5 GHz AP to temper some of the disadvantages and inefficiencies of the ad-hoc networking paradigm.

The 5 GHz AP defines the paths in CANA (*Route Selection*) relying on the information provided by the *Neighborhood Discovery* process.

1) Neighborhood Discovery (ND): The ND process provides information about the 60 GHz topology to the 5 GHz AP by discovering the directly reachable neighbors (one-hop away) of all MTs at 60 GHz inside the HL/2 cell and measuring the quality of the corresponding links. Every MT and the 60 GHz AP participate in ND by exchanging *hello* messages and maintain neighborhood information in the form of a list containing the neighbors and the status of the corresponding links [17]. This information is sent to the 5 GHz AP, which is responsible for the route selection.

The 5 GHz AP decides when ND should be performed. It may be done 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 ND process. The 5 GHz AP sends a broadcast message to inform all MTs inside its coverage area indicating the 60 GHz frequency channel that is used for ND, the time instant at which this procedure is initiated and the transmission schedule of the hello messages.

The frequency channel used for ND is the same as that used by the 60 GHz AP (since the latter also participates in the ND process). Since the MTs may be assigned a different frequency channel when constructing a communication path at 60 GHz, the link state information obtained during the ND process is an approximation (considered to be a good one) of the frequency channel actually used.

The MTs and the 60 GHz AP exchange hello messages in sequential time slots according to a time schedule sent in a message by the 5 GHz AP and based on their MAC IDs, in order to determine their one-hop away neighbors and construct their *link state tables*. After receiving their neighbors' hello messages, every MT and the 60 GHz AP can determine the state of each link with their one-hop away neighbors by measuring the signal-to-noise ratio provided by the physical layer. Depending on the measured link state, different transmission rates may be achieved.

At the end, the MTs forward the collected information to the 5 GHz AP. The 5 GHz AP schedules the transmission of

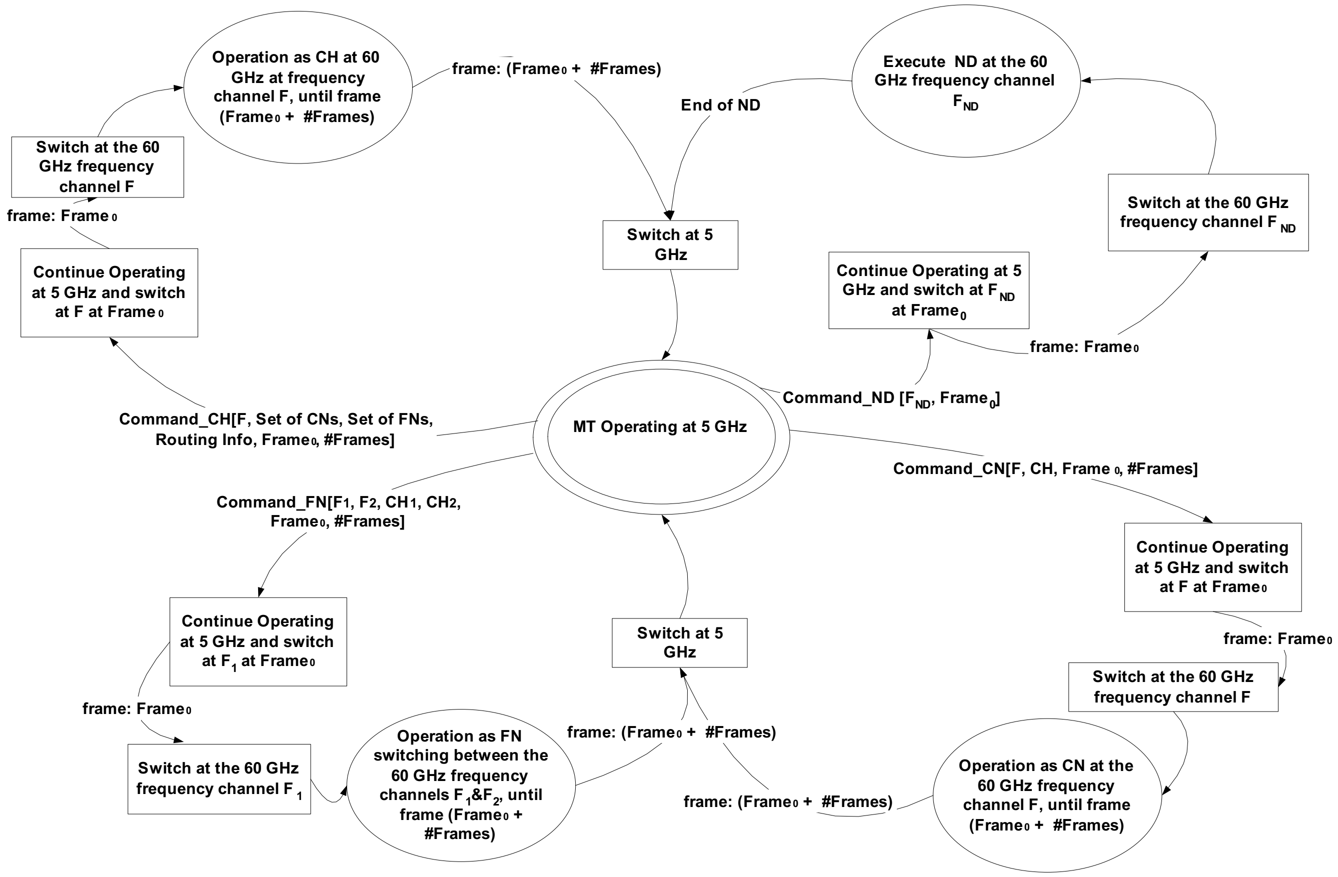

Fig. 2. Different states of a MT in CANA

the MTs' link state tables by reserving bandwidth directly after the end of the exchange of the hello messages, similarly to the standard [11]; the only difference is that MTs do not request for resources before sending their link state tables.

2) Route Selection: The 5 GHz AP makes routing decisions based on information collected during the ND process. This information is stored in the *ND_table* and is updated at the end of ND. The 5 GHz AP manages all resource requests from the MTs inside the HL/2 cell by looking up the *ND_table* and establishing connections either at 5 GHz or at 60 GHz. The involved MTs are assigned the appropriate roles to support these connections. The connections at 5 GHz are more reliable while the 60 GHz links can offer substantially higher rates [16]. Moreover, the availability of the 5 GHz bandwidth is limited in hotspots and consequently paths at 60 GHz will have to be used. The 5 GHz AP selects a path considering the associated link states at 60 GHz. Other quality metrics such as the remaining battery lifetime of the involved MTs and the fact that a CH or a FN consumes more energy may also be considered.

A simple routing algorithm executed by the 5 GHz AP can therefore be specified through the following rules:

1) Whenever a resource request arrives, the 5 GHz AP accesses the *ND_table* to determine the candidate 60 GHz paths for the source-destination pair (60 GHz connectivity check).
2) If there is connectivity at 60 GHz, the most efficient path is identified; efficiency may be defined based on metrics such as: the number of hops, the link states, the need for FNs, the present allocation of resources at 60 GHz and the kind of application to support (required bit rates).
3) (a)If there is no 5 GHz bandwidth available, the most efficient 60 GHz path is utilized.
(b)If there is 5 GHz bandwidth available, it may be utilized instead of the most efficient 60 GHz path identified. Such a decision could be based on criteria such as the quality and bandwidth of the identified 60 GHz path (number of hops, need for a FN, link states, transmission rates, etc.) and the amount of unutilized 5 GHz bandwidth. If the 5 GHz bandwidth is decided to be used, the 5 GHz AP allocates 5 GHz bandwidth to establish the required connection as specified in the standard [11].
4) If there is neither 60 GHz connectivity nor 5 GHz bandwidth available, the connection cannot be estab-

lished and the resource request is resubmitted in the future (rule 1).

When the route is selected, part of the associated frames is reserved for the communication. For a 5 GHz communication the procedure is specified in the standard [11]. When a 60 GHz path is established, the 5 GHz AP sends new messages (commands) defining the lifetime of the path, the participants and their role in the path as well as the resources allocated for this request. The CH can allocate resources inside its cluster as well; this way, MTs can use an already established cluster. The established paths are defined to expire until the next ND process is initiated so that all MTs (and the 60 GHz AP) can participate in it. The TDMA structure of the 60 GHz frame allows for multiple collision-free paths under the control of the assigned CHs. When a 60 GHz path breakage occurs, the participating MTs switch back to the 5 GHz frequency band.

In Figure 2, the different states of a MT in CANA are illustrated.

IV. HIPERLAN/2 MODIFICATIONS TO SUPPORT CANA

This section describes the modifications to the HL/2 protocol stack that are necessary to support CANA. HL/2 specifies a Physical Layer (PHY) and a data link layer consisted of two different layers: the Data Link Control (DLC) that includes the MAC and handles connections, and the Convergence Layer (CL) supporting the interoperability with different higher layers. CL consists of the Common Part Convergence Sublayer (CPCS), which is responsible for segmentation and reassembly, and the Service Specific Convergence Sublayer (SSCS), which efficiently adapts higher layers. The entire protocol stack can be considered as divided vertically in two parts: a Control Plane (CP), for administrative and control operation, and a User Plane (UP) for the transmission of traffic over the established connections.

The enhanced protocol stack for CANA is illustrated in Figure 3. The terms CANA-SSCS and CANA-DLC are used for the particular enhancements that CANA defines at both layers. CANA-SSCS contains all the necessary functionality in order to adapt HL/2 specific packets to Ethernet (ETH) packets and to the packets of the underlying dual mode ad-hoc environment. Data are travelling in UP through CANA-SSCS, CPCS, CANA-DLC, PHY and vice versa. Control information is exchanged through CP. The Node Communication Entity (NCE) exchanges control information with CANA-SSCS and enables the direct exchange of messages between the AP and the MTs.

The enhancements required to support CANA involve: the exchange of control messages between the CP of CANA-SSCS and the CP of CANA-DLC (Ctrl) as well as between NCE and CANA-SSCS, and a peer-to-peer (prtpr) communication between the NCE of two MTs for which there exists a direct link at 60 GHz. The messages exchanged through

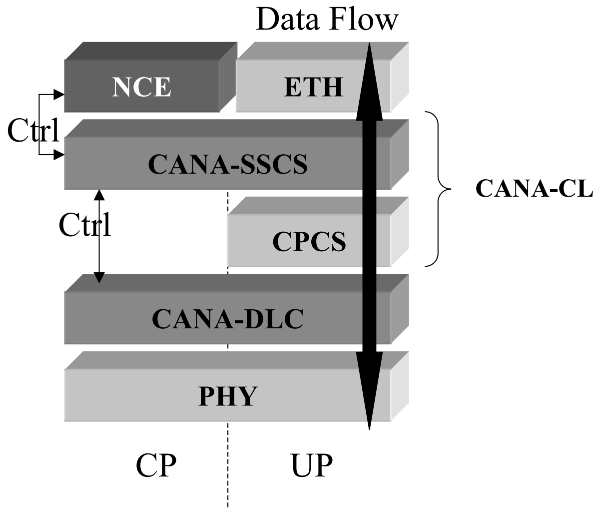

Fig. 3. HiperLAN/2 layer structure modifications to support CANA

the NCE are created or processed by CANA-SSCS. NCE is responsible for realizing this communication and CANA-SSCS utilizes the information carried by these messages.

The modifications inside the layers at the AP are illustrated in Figure 4; at the MTs only the modifications inside the NCE and CANA-DLC are in effect. Each module is depicted as an ellipsis and each table where information is stored as a rectangle. Thin arrows represent sharing of information while thick arrows represent data transmission through UP.

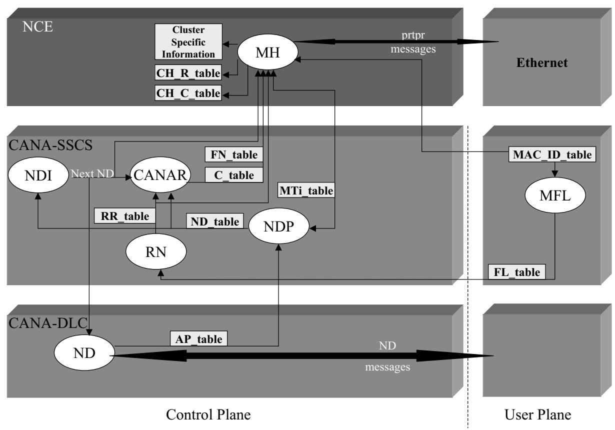

Fig. 4. HiperLAN/2 modifications to support CANA at the AP (only the modifications illustrated in NCE and CANA-DLC are required at the MT)

A. DLC modifications (CANA-DLC)

1) Neighborhood Discovery (ND): This module is responsible for identifying the one-hop away neighbors that the AP and each MT reach at 60 GHz. For the purpose of ND, hello messages at 60 GHz are exchanged with the support of UP. The output of the ND module is the *AP_table* and *MTi_tables*, which contain the one-hop away neighborhood of the AP and the MTs at 60 GHz and are forwarded to CANA-SSCS.

B. SSCS modifications (CANA-SSCS)

1) Monitor Flows (MFL): This module is responsible for monitoring the amount of data to be transmitted for a specific source-destination pair for the required time period (number of frames). This information (called *FL_table*) is updated every time a resource request arrives at the 5 GHz AP.

2) Resource Needs (RN): This module uses the *FL_table* as an input to estimate the resource needs for a certain pair of MTs (*RR_table*).

3) Neighborhood Discovery Processing (NDP): It is responsible for creating the table with the neighborhood information at 60 GHz (called *ND_table*). The input received is the AP's neighborhood information (*AP_table* from CANA-DLC) and the neighborhood information from all MTs (called *MTi_table* for each MT in the HL/2 cell).

4) Neighborhood Discovery Initiator (NDI): It is responsible for deciding on the actual frame that the next ND process will take place.

5) CANA Routing (CANAR): It is responsible for taking decisions and defining the sets of clusters (*C_table*) and FNs (*FN_table*) utilizing information provided by the last ND process (*ND_table*) and the requested resources from the MTs (*RR_table*).

The above modules refer only to the AP. The SSCS at the MT's side needs only minor modifications since most responsibilities are undertaken by the AP.

C. Node Communication Entity (NCE)

1) Message Handler (MH): For the AP, this module is responsible for creating all messages that are sent through the peer-to-peer communication. It uses information that maps the Ethernet addresses to MAC IDs, as well as the output of CANAR (*C_table, FN_table*). The MH informs the MTs about the established clusters and creates the corresponding tables for the operation of the 60 GHz AP as a CH if needed. This information corresponds to the set of the MTs that are present in the 60 GHz AP's cluster (*CH_C_table*) and the useful routing information for intracluster communication (*CH_R_table*). Information regarding the cluster lifetime and the specific frequency channel of cluster operation is also maintained (called *Cluster Specific Information*). Another responsibility of the MH module at the AP is to receive messages from the peer-to-peer communication that include the link state table (*MTi_table*) and the needs for resources (*FLi_table*) from each MT.

For the MT, this module is responsible for receiving and sending messages through the peer-to-peer communication and information regarding cluster establishment. The MH creates the corresponding tables for its operation as a CH (whenever it is needed). This information corresponds to the set of the MTs that are present in its cluster at 60 GHz (*CH_C_table*) and the routing information that is useful for intracluster communication (*CH_R_table*). Specific information in case the MT is a CN or a FN (cluster lifetime, the specific frequency channel, corresponding CH or CHs, etc.) is also maintained (*Cluster Specific Information*).

V. CANA Evaluation

The objective of this section is to show, through a qualitative analysis, when the use of the second mode of operation in CANA and/or the intercluster communication are beneficial. Let the overhead paid for CANA be referred to as the *cost*. This cost is expected to be compensated by the second mode of operation and let this compensation be referred to as the *benefit*. The term *gain* refers to the comparative advantage of the benefits over the costs and will be defined appropriately for each case in this section.

For the rest, the overhead introduced under CANA by the standard operation at 5 GHz (i.e. association, disassociation, connection setup, etc.), will not be considered. It is assumed that MTs are normally operating at 5 GHz and the gain will be estimated with respect to the additional cost introduced by supporting the 60 GHz mode of operation.

A. Evaluation of the dual mode of operation

Let N be the number of MTs present in the network. Let α be the benefit per frame per MT for a MT that is operating at the 5 GHz mode of operation. During the ND process, a MT is absent from the 5 GHz mode of operation and, therefore, this benefit is becoming a cost needed for the execution of ND; the same holds for a MT that due to certain mobility conditions maintains no connectivity any more with the CH of the corresponding cluster. The total cost for all MTs for the entire ND process is $N\alpha f_{ND}$. Let β be the benefit for those MTs that are operating at the 60 GHz mode of operation and let N_{CL} be the number of these MTs ($N_{CL} \leq N$). Let N'_{CL} be the average number of MTs that have switched at 60 GHz but cannot use the resources (primarily due to lost connectivity while being at 60 GHz). Obviously, the benefit is $(N_{CL} - N'_{CL})\beta f_{CL}$ (operation at 60 GHz) and the cost is $N_{CL}\alpha f_{CL}$ (N_{CL} nodes are not benefitted by the 5 GHz mode of operation).

Let G_{CANA} be the gain examined for the dual mode evaluation, or $G_{CANA} = \frac{(N_{CL}-N'_{CL})\beta f_{CL}}{N\alpha f} - \frac{N_{CL}\alpha f_{CL}}{N\alpha f} - \frac{N\alpha f_{ND}}{N\alpha f}$. Let c be a constant such that $\beta = c\alpha$ and $c > 1$ (note that $\beta > \alpha$ since the 60 GHz links may offer higher rates than the traditional 5 GHz HL/2 technology). The requirement is that the gain is positive ($G_{CANA} > 0$) and it is known that $f = f_{New} + f_{ND}$.

$$G_{CANA} = (c-1)\frac{N_{CL}}{N}\frac{f_{CL}}{f_{New}+f_{ND}} - c\frac{N'_{CL}}{N}\frac{f_{CL}}{f_{New}+f_{ND}} - \frac{f_{ND}}{f_{New}+f_{ND}}. \quad (1)$$

From Equation (1), it may be concluded that G_{CANA} increases as c increases ($N_{CL} > N'_{CL}$). G_{CANA} also increases as the number of nodes that belong in clusters, $\frac{N_{CL}}{N}$, increases. G_{CANA} decreases as the ND overhead $\frac{f_{ND}}{f_{New}+f_{ND}}$

Table 1
SUMMARY OF PARAMETERS

Parameter	Description
N	Number of MTs present in the network
N_{CL}	Number of MTs that switch at 60 GHz
N'_{CL}	Average number of MTs that have switched at 60 GHz but have lost connectivity
α	Benefit operating at 5 GHz
β	Benefit operating at 60 GHz
f	Number of frames between two consecutive ND processes
f_{New}	Number of frames between the end and the beginning of consecutive ND processes
f_{CL}	Number of frames that a cluster is active
f_{ND}	Number of frames required by a ND process
f_k	Number of frames that the path in an intercluster communication is available
c	Constant such that $\beta = c\alpha$
k	Number of clusters between two MTs
G_{CANA}	Gain for the dual mode of operation
$G^k_{S\to D}$	Gain for the intercluster communication
p	Probability that connectivity at 60 GHz is lost

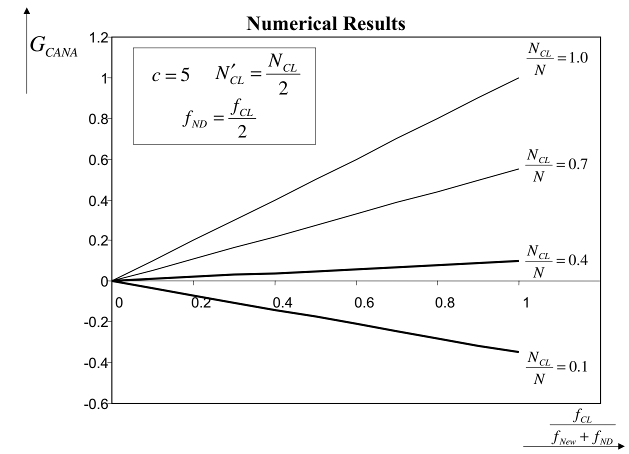

Fig. 5. Examining the gain for the dual mode of operation (G_{CANA})

increases (the ND overhead is defined as the fraction of time during which ND is performed). It is interesting to note that G_{CANA} may increase or decrease as $\frac{f_{CL}}{f_{New}+f_{ND}}$ increases, according to the value of $\frac{N_{CL}}{N}$. This is depicted in Figure 5. When $\frac{N_{CL}}{N}$ is comparably small, G_{CANA} is negative since the cost paid is increased compared to the benefit when using the 60 GHz mode of operation. Note that for this case, $\frac{N'_{CL}}{N}$ is a function of $\frac{N_{CL}}{N}$ and comparably high ($N'_{CL} = \frac{N_{CL}}{2}$).

B. Evaluation of intercluster communication

The intercluster communication greatly suffers from the MTs' movement, resulting to a smaller benefit. The aim here is to present a qualitative evaluation of the intercluster communication and show when it may be allowed between certain MTs.

Consider the general case where one (source) MT (MT_S) needs to send data to another (destination) MT (MT_D). Suppose that both MTs are switched at 60 GHz and k clusters are between them. Assuming that both MTs are neither CHs nor FNs, a path of $2k$ hops (direct links between two MTs) exists in-between. Therefore, data from MT_S need at least $2k$ frames before reaching MT_D, as it may be seen in Figure 6.

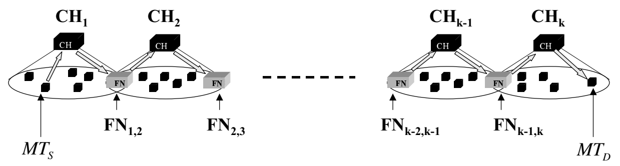

Fig. 6. Intercluster communication between two MTs (MT_S and MT_D) separated by k clusters connected by $(k-1)$ FNs

The first observation is that if k is large, the intercluster communication is not an efficient solution for applications with time constraints. If the latter is the case, then both MTs should have used the 5 GHz mode of operation. Another observation is that the FN (and the CH) should be capable of storing large amounts of data requiring large buffers (especially for the FN that is partially present in a cluster). This might be a real problem given that all MTs are potential CHs and FNs and the device's cost and complexity increases rapidly. Partial improvement may be introduced if another MT could play the role of a second FN (simultaneously) so that there is always one FN at each cluster during the lifetime of an intercluster communication.

Let f_k be the number of frames during which the path between MT_S and MT_D (denoted also by $MT_S \to MT_D$) exists. Clearly, as k and/or the mobility increases, f_k decreases. The number of frames that the k clusters are active is assumed to be f_{CL}. It is satisfied that $f_k \leq f_{CL}$. Note that the MT_D will start receiving data $2k$ frames after the switching at 60 GHz; the benefit is $(f_k - 2k)\beta$. If both MTs were at the 5 GHz mode of operation, the benefit would have been $f_{CL}\alpha$. Consequently, the intercluster gain, $G^k_{S\to D}$, is given by $G^k_{S\to D} = \frac{(f_k-2k)\beta}{f_{CL}\alpha}$. The requirement is $G^k_{S\to D} > 1$.

$$G^k_{S\to D} = c\frac{f_k - 2k}{f_{CL}}. \quad (2)$$

As it can be seen from Equation (2), $G^k_{S\to D} < 0$ if $f_k < 2k$. This is expected since, for this case, no data are able to arrive at the destination (so, data remain in the intermediate nodes and are forwarded to the AP as soon as the MTs switch back to the 5 GHz mode of operation). Clearly, $G^k_{S\to D}$ increases with c but this is not beneficial if $f_k < 2k$. It also appears that for small values of f_{CL}, $G^k_{S\to D}$ is high. This is not actually the case given the constraint $f_k \leq f_{CL}$. Consequently, small values of f_{CL} force smaller values of f_k resulting to lower values for $G^k_{S\to D}$.

As k increases, f_k decreases and, therefore, the term $f_k - 2k$ decreases rapidly. f_k decreases as the mobility increases. For certain mobility conditions, each hop can be characterized by a probability that the connectivity is lost. Let this probability be denoted by p and be common for all hops. The probability that the $2k$-hop path is not broken is then $(1-p)^{2k}$. The latter is closely connected to f_k and shows the exponential dependency of f_k on k. For this reason, the numerical results presented in Figure 7 have been obtained assuming that $f_k = f_{CL}e^{-k}$ (only for demonstration purposes), which incorporates the exponential dependency and satisfies the constraint $f_k \leq f_{CL}$.

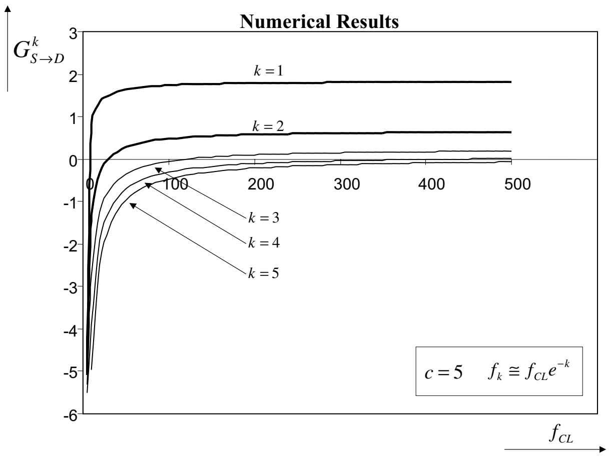

Fig. 7. The intercluster gain ($G^k_{s\to D}$) as a function of f_{CL} (f_k is demonstrated using $f_k = f_{CL}e^{-k}$)

Figure 7 shows that low values of k are desirable while low values for f_{CL} are not. Note that rather large values of f_{CL} do not provide any obvious advantage and converge to a certain value ($\lim_{f_{CL}\to\infty} G^k_{s\to D} = e^{-k}$ for $f_k = f_{CL}e^{-k}$).

Consequently, for an efficient intercluster communication, a small number of clusters between the MTs is required and the cluster lifetime, as well as the path lifetime, needs to be sufficiently large.

VI. Simulation Results

The new frequency at 60 GHz offers ample bandwidth to users while, at the same time, its characteristics (line-of-sight constraints and short communication distances) provide for private and interference-limited communications with increased spatial reuse – like WPANs. CANA's performance and effectiveness is affected by the additional required control overhead. The overhead of CANA is due to the ND process and the extra messages needed to establish a 60 GHz connection. The ND process constitutes the main control overhead in CANA since it requires that the system remains inactive until it is completed and for this reason it should not be executed frequently. On the other hand, this process needs to be repeated frequently as it provides useful information for the establishment of paths at 60 GHz. Clearly, there is a trade-off here that needs to be considered carefully. In [18], the impact of different techniques for switching between the two frequency bands on CANA's effectiveness is evaluated.

The results presented in this article have been derived from ns-2 simulations [19]. They are not comprehensive by any means but their purpose is to illustrate insights, potential gains and highlight trade-offs. Simulations were run for 300 seconds. The results were averaged over 50 runs for each scenario.

Four different levels l of 60 GHz communication have been defined and considered inside a HL/2 cell based on the physical distance (in m) between the MTs; $l \in \{6, 8, 12, 15\}$. Two MTs that are d meters apart can establish a level l communication as long as $0.8l \leq d \leq 1.2l$. A sequence of n MTs each of which is away from the preceding MT by some distance in $(0.8l, 1.2l)$ is said to form a level l path of length $(n-1)$ hops.

Mobility has been modelled using the *random waypoint model* in a rectangular field. A 100m X 100m field has been considered for a HL/2 cell with 50 MTs. Each MT starts its journey from a random location and moves toward a random destination at a randomly chosen speed v (uniformly distributed between 0 and v_{max} (in m/sec), where $v_{max} \in \{1, 3, 5, 10, 15, 20\}$. Once the destination is reached, another random destination is targeted after a pause. All results that are presented here correspond to a pause time of 0sec to illustrate the most dynamic environments.

A. Mean lifetime of the 60 GHz multi-hop paths

One of the main concerns when establishing the 60 GHz paths is the high probability of link failures due to their short lifetime.

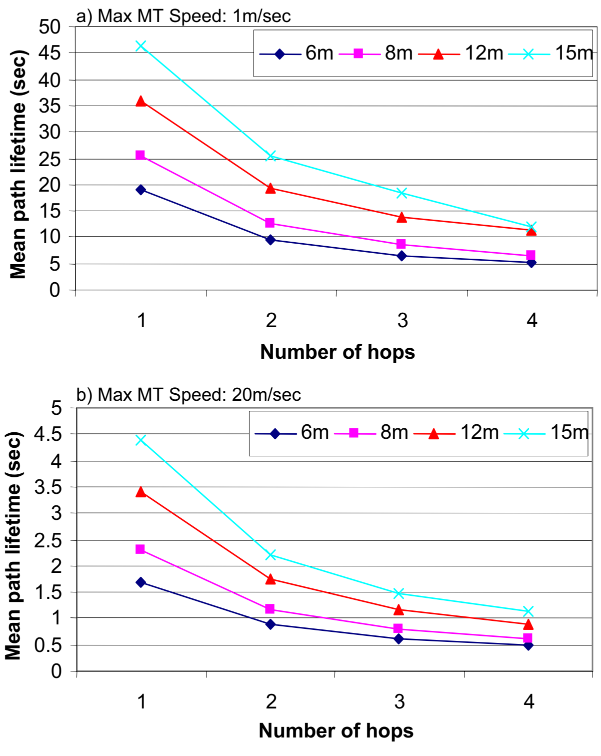

Fig. 8. Mean path lifetime versus the number of hops

Figure 8 presents the mean lifetime of paths of different levels l as a function of their length (in number of hops) and for max MT speed of 1m/sec and 20m/sec; paths of up to four hops are considered. As expected, the graph shows that the mean path lifetime decreases with the length of the path and increases with the communication level. It decreases by a factor of one half for two-hop paths and significantly less for longer-hop paths. While higher communication level paths last longer on the average, it should be noted that the associated power consumption increases and the potential for higher rates decreases. If the latter two factors are not of a concern, then in such an environment higher communication levels should be considered to construct longer-living paths. Notice that paths of level 15m last more than 2-3 times longer than those of level 6m, depending on their length.

The impact of MT speed on the mean path lifetime is shown in Figure 9. It may be observed that under low max MT speeds (1-5m/sec) the decrease rate of the mean path lifetime is much higher than under higher speeds (10-20m/sec).

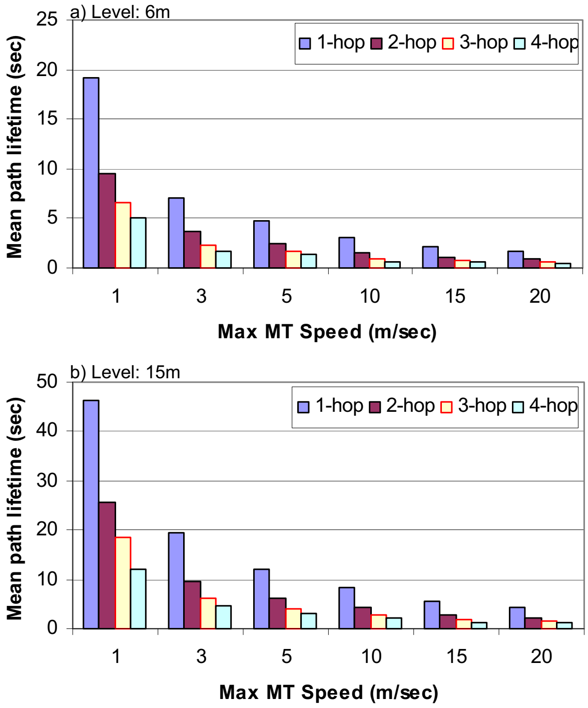

Fig. 9. Mean path lifetime versus MT speed

B. Efficiency of the 60 GHz multi-hop paths

The previous results indicate that the mean lifetime of paths with two or more hops is rather low especially in cases of high mobility. In addition, in multi-hop paths the assigned CHs and FNs reduce the utilization of the available resources (lower end-to-end bit rates), since they spend only part of their time to communicate with each of their neighboring MTs. The reduction of resource utilization is higher for the FNs since they should switch between frequency channels at 60 GHz and be synchronized with the CHs' frames. In view of the previous, it would be interesting to determine the amount of data that these paths actually support.

Studies of baseband algorithms in [16] have shown that transmission rates between 13,3 Mbps and 720 Mbps can be achieved at 60 GHz depending on the constellation size, the channel bandwidth and the communication distance between the source and the destination. Two different baseband parameter sets were used resulting in a low and a high transmission rate. In Figure 10, the achieved rate is illustrated for two levels of communication (15m and 6m); it is normalized by the maximum physical layer transmission rate of 54 Mbps in HL/2 (the actual transmission rate for the user does not exceed 25 Mbps).

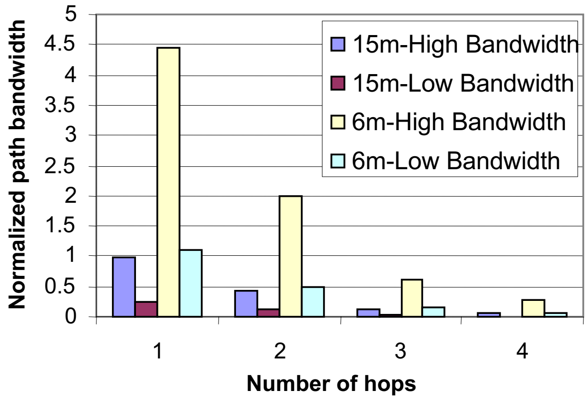

Fig. 10. Efficiency of the 60 GHz multi-hop paths

Even under the low parameter sets, multi-hop paths can achieve high end-to-end bit rates. Considering that Figure 10 refers to a single path, it can be concluded that CANA can achieve a high aggregate throughput gain due to spatial reuse. Moreover, even four-hop paths can significantly contribute to this throughput gain, especially in the case of the parameter sets achieving high bit rates at 60 GHz (lower communication ranges). By multiplying corresponding results from Figure 9 and achieved bit rates at 60 GHz, one can easily determine the average amount of data that can be transmitted over the mean path lifetime. For instance, this amount is 162 Mbits for a three-hop, level 6m path for max MT speed of 1m/sec under the high rate scheme.

C. ND overhead

In order to take advantage of the available 60 GHz paths, the information obtained by the ND process is necessary. In Figures 11 and 12, the dependence of the overhead of the ND process from the number of hops that constitute a path, the number of MTs inside the cell and mobility is shown. The ND overhead is defined as the fraction of time during which ND is performed (including the required switching time to the frequency channel of ND [17]). The number of MTs inside a cell affects the ND overhead since it affects its duration. We assume that ND is periodically performed with such a period that more than 90% of the calculated paths do not break between two consecutive NDs for the specific speed and communication level. Figure 11 illustrates

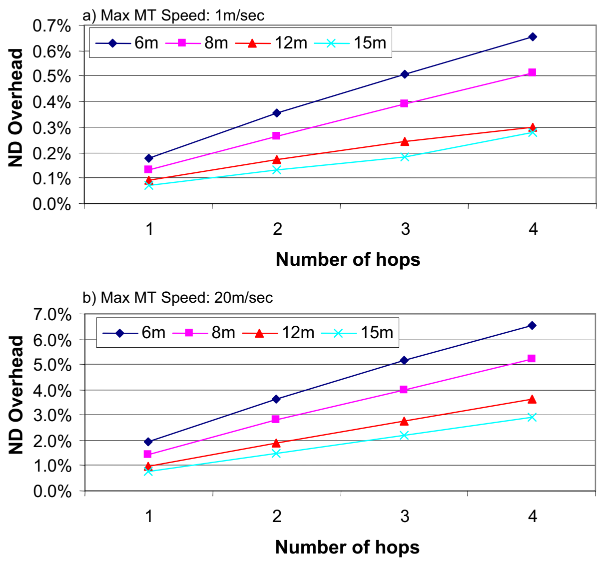

Fig. 11. ND overhead versus the number of hops (for 200 users in a cell)

the cases for a max MT speed of 1m/sec and 20m/sec and for 200 users in the cell. Since the paths that consist of more hops have shorter lifetime, more overhead is required to support them (the ND process is performed more frequently).

For the case of 200 users, the minimum (maximum) ND overhead is calculated to be 0.176% (below 6.632%) for one-hop (four-hop) communication of level 15m (6m) and max MT speed of 1m/sec (20m/sec). The ND overhead is lower when the number of users decreases. In Figure 12, the ND overhead of four-hop paths of level 6m (most vulnerable) is illustrated for all max MT speeds considered. As the max MT speed increases, more overhead is required to maintain 90% of the paths due to the higher probability of link failure.

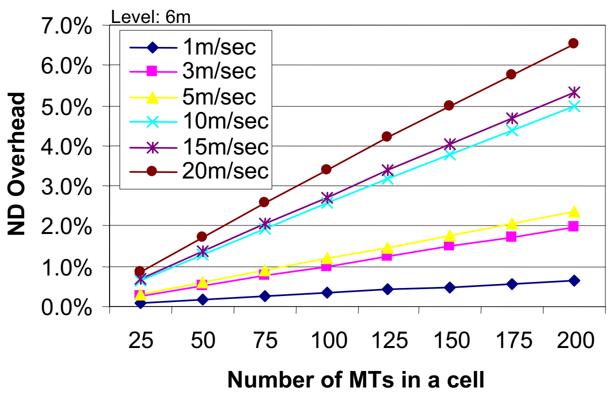

Fig. 12. ND overhead of four-hop paths of level 6m versus the number of MTs inside a cell (for different MT speeds)

D. Efficiency of CANA

The remaining results show the efficiency of the ND process in terms of the number of source-destination pairs that can be supported between two consecutive NDs. The number of source-destination pairs measures the capability of CANA to satisfy traffic requirements inside the cell. The more source-destination pairs CANA is capable of managing, the higher potential throughput achieved by the WLAN. Some of the results are shown in Figures 13 and 14.

In Figure 13, the number of source-destination pairs of each level of communication is illustrated as a function of the number of hops in a path for max MT speeds of 1m/sec and 20m/sec and for 50 MTs inside a cell. As the number of considered hops or the speed increases, more source-destination pairs can be supported by CANA at higher overhead. For short distances (6m and 8m), the increase of source-destination pairs is not apparent in the figure since there are only few available paths.

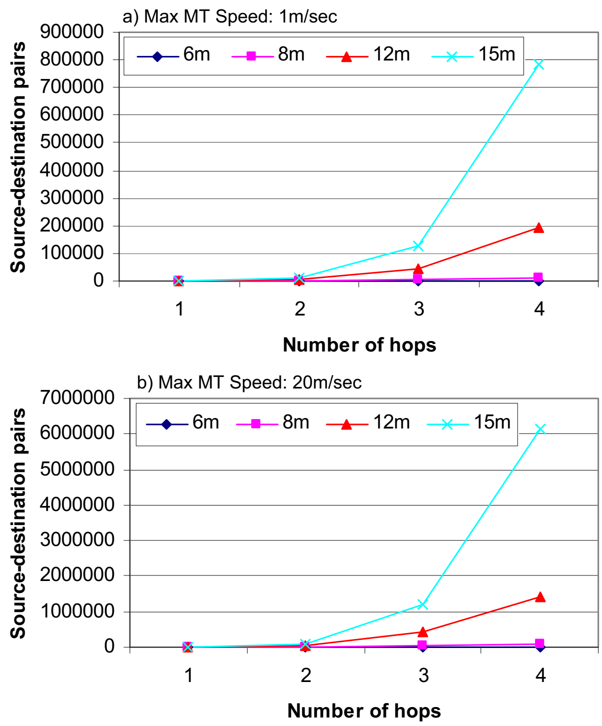

Fig. 13. Number of source-destination pairs versus the number of hops

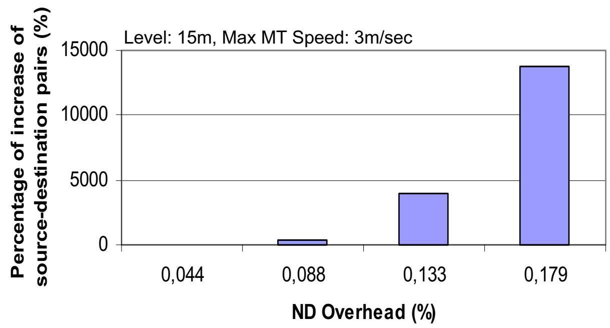

Fig. 14. Increase of source-destination pairs versus ND overhead

The source-destination pairs shown in the previous figure require different ND overhead to be supported. For all cases considered, this overhead is below 7% as mentioned earlier.

In Figure 14, the percentage of increase of the source-destination pairs as a function of the overhead of the ND process is depicted for the case of 3m/sec, for the paths of level 15m and for 50 MTs inside a cell. It is shown that a low increase on the induced ND overhead can achieve a huge increase on the number of source-destination pairs (by establishing paths that consist of more hops).

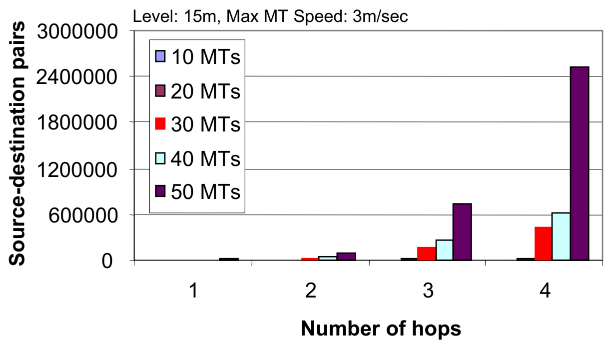

Fig. 15. Number of source-destination pairs versus the number of hops and the number of MTs inside a cell

Simulations were conducted for 10, 20, 30, 40 and 50 MTs inside a cell for the communication level of 15m and max MT speed of 3m/sec, to measure the number of source-destination pairs. As depicted in Figure 15, in low-density cells the number of supported source-destination pairs is very limited to the point of not worthing the associated ND overhead. Especially for the paths consisting of one or two hops, the number of source-destination pairs in low-density cells is negligible (but not zero as may appear in Figure 15).

The number of destinations multi-hop paths may reach represents the level of connectivity; as the speed increases, more paths can be established but, at the same time, their lifetime is shorter. While short distances provide for the potential for higher bit rates (and capacity) inside the cell, connectivity may be compromised and network partitions occur. Higher ND overhead is required in order to support more source-destination pairs (higher density or mobility); on the other hand, CANA cannot be effective in case of low number of users inside the cell – since there are no paths available to connect a sufficient number of nodes.

VII. Conclusions

In this article, a WLAN capable of operating in a traditional (5 GHz) and a new (60 GHz) frequency bands is considered. The Centralized Ad-hoc Network Architecture (CANA) is proposed that coordinates resource usage in both frequency bands and effectively incorporates the ad-hoc (multi-hop) networking paradigm to offload the traditional 5 GHz band through spatial reuse and very high rate transmissions enabled at 60 GHz over shorter distances.

CANA may be viewed as one of the first attempts to blend different networking paradigms (cellular and ad-hoc) to develop wireless networks capable of supporting a wide range of demanding applications (in terms of bit rates), platforms (integration of WLANs and WPANs) and environments (hotspots). To investigate the potential of CANA in supporting high-rate applications and offloading traditional WLANs in hotspots, some relevant quality metrics have been considered, analytical expressions have been derived and simulations have been conducted. The ad-hoc networking paradigm is not only more effective because it is infrastructure-assisted, but it can also support higher bit rates at the new frequency. Multi-hop paths (beyond two hops) can be – in principle – short-living in a dynamic environment of high user mobility. Results suggest, though, that the mean path lifetime is such that it allows for a large amount of information exchange under the very high transmission rates that are feasible in the 60 GHz frequency band at low overhead, even over multi-hop paths or in case mobility is high.

Acknowledgements

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References

[1] M. Frodigh, S. Parkvall, C. Roobol, P. Johansson, and P. Larsson,"Future-Generation Wireless Networks", in *IEEE Personal Communications Magazine*, vol. 8, no. 5, October 2001, pp. 10-17.

[2] Ch. E. Perkins, *Ad Hoc Networking*, Addison-Wesley, United States of America.

[3] M. Buddhikot, G. Chandranmenon, S. Han, Y. W. Lee, S. Miller, and L. Salgarelli, "Integration of Wireless LAN and 3G Wireless – Design and Implementation of WLAN/CDMA2000 Interworking Architecture", in *IEEE Communications Magazine*, vol. 41, no. 11, November 2003.

[4] H. Y. Hsieh and R. Sivakumar, "On Using the Ad-hoc Network Model in Cellular Packet Data Networks", in *Proc. ACM MOBIHOC 2002*, Lausanne, Switzerland, June 2002.

[5] Y. D. Lin and Y. C. Hsu, "Multi-Hop Cellular: A New Architecture for Wireless Communications", in *Proc. IEEE INFOCOM 2000*, Tel Aviv, Israel, March 2000.

[6] A. Panagakis, E. Balafoutis, and I. Stavrakakis, "Study of the Capacity of Multi-hop Cellular Networks", in *Proc. Quality of Future Internet Services (QoFIS) 2003*, Stockholm, Sweden, October 2003.

[7] H. Y. Hsieh and R. Sivakumar, "Performance Comparison of Cellular and Multi-hop Wireless Networks: A Quantitative Study", in *Proc. ACM SIGMETRICS 2001*, Cambridge, MA, USA, June 2001.

[8] K. Jayanth Kumar, B. S. Manoj, and C. Siva Ram Murthy, "MuPAC: Multi-Power Architecture for Cellular Networks", in *Proc. PIMRC 2002*, Lisbon, Portugal, September 2002.

[9] M. Lott, M. Weckerle, W. Zirwas, H. Li, and E. Schulz, "Hierarchical Cellular Multihop Networks", in *Proc. EPMCC 2003*, Glascow, Scotland, April 2003.

[10] M. de Courville, S. Zeisberg, M. Muck, and J. Schonthier, "BROADWAY – the Way to Broadband Access at 60 GHz", in *Proc. IST Mobile Summit 2002*, Thessaloniki, Greece, June 2002.

[11] M. Johnson, "HiperLAN/2 - The Broadband Radio Transmission Technology Operating in the 5 GHz Frequency Band", available via the HiperLAN/2 Global Forum, *http://www.hiperlan2.com*.

[12] ETSI, TS 101 761-4, "Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Data Link Control (DLC) Layer; Part 4: Extension for Home Environment", Sophia Antipolis, France, 2000.

[13] ARIB STD-T70, "Low Power Data Communication System / Broadband Mobile Access Communication System (HiSWANa)", version 1.0, December 2000, more information at *http://www.arib.or.jp/mmac*.

[14] P. Smulders, "Exploiting the 60 GHz Band for Local Wireless Multimedia Access: Prospects and Future Directions", in *IEEE Communications Magazine*, vol. 40, no. 1, January 2002, pp. 140-147.

[15] IST-2001-32686 BROADWAY, "WP1, D2 – Functional System Parameters Description", November 2002, project deliverable available at *http://www.ist-broadway.org/documents/broadway-WP1-D2-v1_0.pdf*.

[16] IST-2001-32686 BROADWAY, "WP3, D7 – Algorithm Enhancement Definition", November 2002, project deliverable available at *http://www.ist-broadway.org/documents/broadway-WP3-D7a-v1_0.pdf*.

[17] A. Vaios, K. Oikonomou, and I. Stavrakakis, "A Centralized Routing Scheme Supporting Ad Hoc Networking in Dual Mode HIPERLAN/2", in *Proc. IST Mobile & Communications Summit 2003*, Aveiro, Portugal, June 2003.

[18] K. Oikonomou, A. Vaios, S. Simoens, P. Pellati, and I. Stavrakakis, "A Centralized Ad-Hoc Network Architecture (CANA) Based on Enhanced HiperLAN/2", in *Proc. PIMRC 2003*, Beijing, China, September 2003.

[19] The Network Simulator *ns-2*, *http://www.isi.edu/nsnam/ns/*.

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