Incorporation of the short-range multi-hop communication model in infrastructure-based wireless local area networks

Athanasios Vaios*

National and Kapodistrian University of Athens
Department of Informatics and Telecommunications
avaios@di.uoa.gr

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 overhead of CANA is rather low if one takes into account the profits of such architecture.

Keywords: multi-hop path, performance, throughput, overhead, model, analysis.

1 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 tech-

* Dissertation Advisor: Ioannis Stavrakakis, Professor

nologies 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) provides for a scalable network architecture that is based on current 5 GHz WLAN technologies equipped with extensions in the 60 GHz frequency band 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.

The rest of the article is organized as follows. The proposed architecture, CANA, is presented in section 2. In section 3, the modifications needed in order to apply CANA in HiperLAN/2 (HL/2) are defined. Finally, some simulation results are presented and discussed, followed by conclusions.

2 The Centralized Ad hoc Networking Architecture (CANA)

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 [3-10].

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.

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 due to the fact that 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.

2.1 Dual Mode of Operation

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, as explained later. Association with and connections at 5 GHz are established as described in the HL/2 standard [11].

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.

CANA defines three different roles for the MTs that operate at 60 GHz that are all assigned by the 5 GHz AP; that of a ClusterHead (CH), which controls the frame at 60 GHz, that of a Forwarder Node (FN), which allows for the interconnection of different clusters and that of a Common Node (CN), which simply participates in the created cluster. This distinction is based on the different functionalities that a role encompasses and not on different hardware capabilities. 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. Figure 1 depicts a time instant of CANA showing the three different roles of a MT at 60 GHz.

2.1 Routing

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 5 GHz 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.

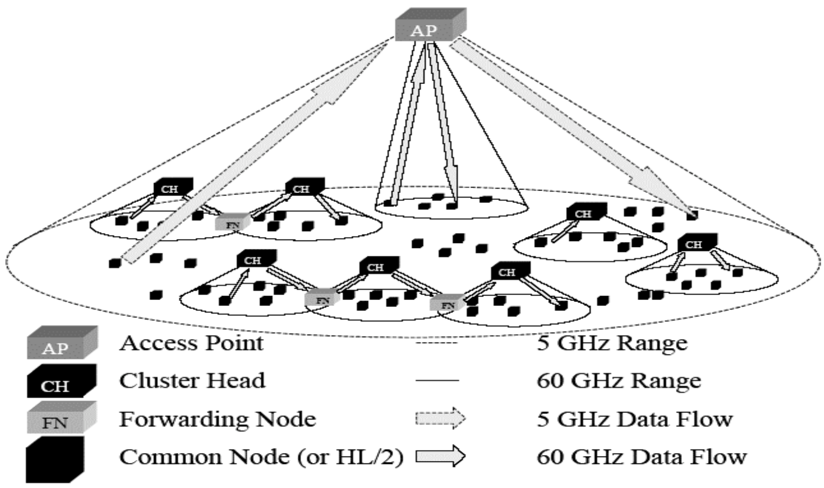

Figure 1: A time instant of CANA

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.

- *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 GH 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 its neighbors' hello messages, a 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 GH AP. The 5 GH AP schedules the transmission of 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.

- *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. 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.

3 HiperLAN/2 modification 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 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 between which there exists a direct link at 60 GHz. The messages exchanged through 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 2; at the MTs only the modifications inside 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.

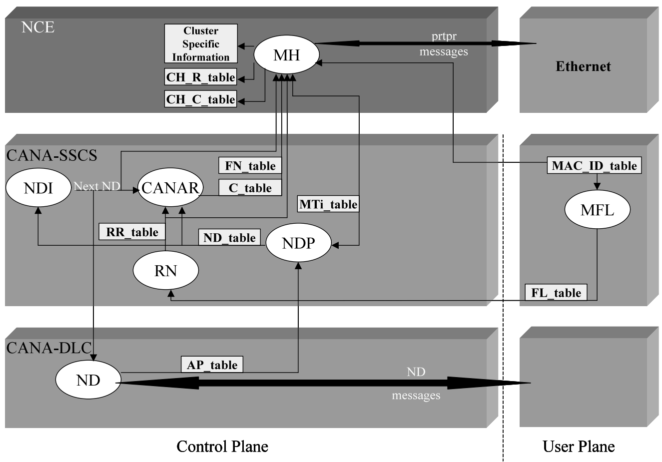

Figure 2: HiperLAN/2 modifications to support CANA at the AP (only the modifications illustrated in NCE and CANA-DLC are required at the MT)

3.1 DLC modifications (CANA-DLC)

This module is responsible for identifying the one-hop away neighbors that the AP and each MT reaches 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.

3.2 SSCS modifications (CANA-SSCS)

- *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.

- *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*).

- *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 its own 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).

- *Neighborhood Discovery Initiator (NDI)*

It is responsible for deciding on the actual frame that the next ND process will take place.

- *CANA Routing (CANAR)*

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

3.3 Node Communication Entity (NCE)

- *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 intra-cluster 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 intra-cluster communication (*CH_R_table*). Specific information when 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).

4 Performance issues in CANA

The results presented here 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 5 runs for each scenario.

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

Mobility has been modeled 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} *Є {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 0 sec to illustrate the most dynamic environments.

In order to take advantage of the available 60 GHz paths, the information obtained by the ND process is necessary. In Figure 3, 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.

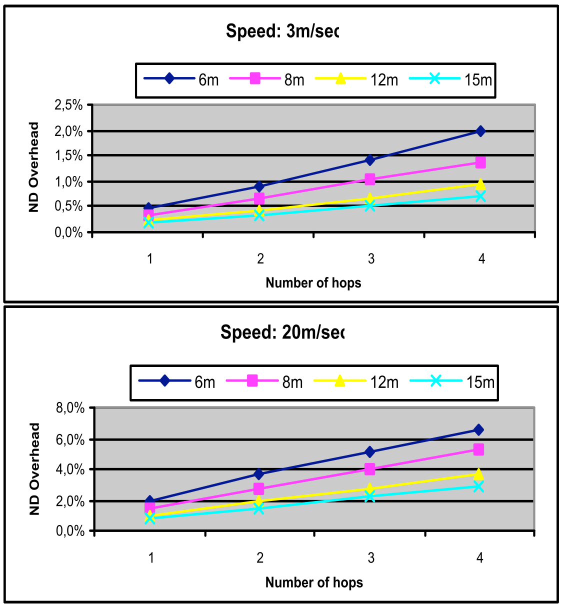

Figure 3: ND overhead versus the number of hops (for 200 users in a cell)

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 3 illustrates the cases for a speed of 3m/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).

The minimum (maximum) ND overhead is calculated to be approximately 0,176% (below 7%) for the case of 200 users for one-hop (four-hop) communication of level 15m (6m) and MT speed of 1m/sec (20m/sec).

5 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 adhoc (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). 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.

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. IEEE 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. Schönthier, “BROADWAY – the Way to Broadband Access at 60 GHz”, in *Proc. IST Mobile Summit*, Thessaloniki, Greece, June 2002.
11. M. Johnson, “HiperLAN2 – The Broadband Radio Transmission Technology Operating in the 5 GHz Frequency Band”, Technical Report, HiperLAN2 Global Forum, 1999.
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, “WP2, 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 System”, in *Proc. IST Mobile Summit 2003*, Aveiro, Portugal, June 2003.
18. K. Oikonomou, A. Vaios, S. Simoens, P. Pellati, and I. Stavrakakis, “Centralized Ad-Hoc Network Architecture (CANA) Based on an Enhanced HiperLAN/2 System”, in *Proc. PIMRC 2003*, Beijing, China, September 2003.
19. The Network Simulator *ns-2,* http://www.isi.edu/nsnam/ns/
20. 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.