

A cross-layer feature for an efficient forwarding strategy in wireless ad hoc networks

Lamia Romdhani and Christian Bonnet
Mobile communication department, Institut Eurécom
{romdhani, bonnet}@eurecom.fr

Abstract

In this work, we present a Cross-Layer Forwarding Strategy (CLFS), which is based on the cooperation between the new IEEE 802.11e MAC protocol (EDCA) and the On-Demand AODV routing protocol. The proposal aims to minimize the number of Forwarding nodes (FN) by hop, in the network. By this way, we decrease the contention amount and we improve the medium utilization. The selection of FN is based on maximum battery level and queue occupancy. These informations are injected into routing requests and replies crossing nodes in the network. Then, each node is able to select the FN that will participate in path establishment. In order to maintain a fair node capability, the forwarding procedure is dynamically distributed and assigned to nodes in the network. Moreover, an Adaptive Transmission Opportunity (ATXOP) mechanism, is derived from the EDCA. It aims to share the transmission channel fairly according to traffic load of nodes.

We demonstrate that CLFS has good network performance, specially in term of throughput, that can be significantly improved. Moreover, it achieves a high degree of fairness among applications.

1 Introduction

Current layered design paradigm is inflexible and sub-optimal for wireless networks. A good network planning is required in order to meet the performance expectations especially when IEEE 802.11 is used with real-time applications. Indeed, multimedia processing and transmission are delay sensitive that require considerable battery power as well as network bandwidth. Furthermore, the routing, mac, and physical protocols that support QoS must be adaptive and cooperative to cope with the time-varying topology and time-varying network resources.

Enhanced Distributed Contention Access (EDCA) is a contention-based HCF channel access specified in IEEE 802.11e [3]. The proposed scheme provides capability for up to four types of traffic classes. It assigns a short CW_{min} , CW_{max} , and $AIFS$ to classes that should have higher priority in order to ensure that in most cases, higher-priority classes will be able to transmit before the lower-priority ones. To decrease delay, jitter, and achieve higher medium utilization, packet bursting is proposed in IEEE 802.11e standard. So, once a station has gained access to the medium, it can be allowed to send more than one frame without contending for the medium again. After getting access to the channel, the station is allowed to send as many frames it wishes as long as the total access time does not exceed a certain limit ($TXOP_{Limit}$) and no collision occurs. There is no need to use RTS/CTS frames for the transmitted packets. The

$TXOP_{Limit}$ parameter is fixed and could not react to traffic load variation and medium utilization. In this paper, we propose to adapt EDCA parameters to node load while decreasing the contention amount by reducing the number of forwarding nodes thought routing process.

In mobile ad hoc networks (MANET), network services are fulfilled by the cooperation of all nodes instead of pre-deployed facilities. Due to the limited radio transmission range, data packets are usually forwarded by multiple intermediate nodes before they reach the destination. Packet transmission does not come for free. In addition to the bandwidth and computational cost, energy is spent by each Forwarding Nodes (FN). Furthermore, when the number of FN increases in the same hop, the contention amount increases and affects the application performance. We believe that minimizing the effective of FN can enhance well the medium utilization and reduce collisions. These nodes constantly use more energy than others. If this trend continues, these nodes will die much earlier than the others and will cause the disconnection of the network. To overcome this problem, we allow the intermediate nodes to redirect the route on each hop and form cooperative coalitions on the fly. Hence, the forwarding activity is balanced between nodes in order to provide a fair resource consumption. A level N hop, a node chooses one of its level N-1 neighbors for forwarding data packets based on its battery level and queue occupancy. Moreover, different weights w_i are assigned to node i in the network according to their load. This parameter is used to tune and adapt MAC layer parameter values, as Contention Window (CW) and TXOP duration. This leads to high medium access probability for FN.

The remainder of this paper is organized as follows. In Section 2, we review the most important works that have been done so far to enhance MANET performance through the use of cross layer architecture. The description of the proposed CLFS cross-layer model is given in Section 3. Simulation methodology and performance evaluation of our proposal are detailed in Section 4. Section 5 concludes the paper by summarizing results and outlining future works.

2 Related works

The co-operation between layers to enable performance enhancement is very important and useful in wireless ad-hoc networks. The global objective of such co-operation is to achieve a reliable communication-on-the-move in highly dynamic environments as well as QoS provisioning. Numerous works have been presented in the open literature that introduce several coupling ways and solutions between different communication layers as we discussed in [9]. Hereafter, we review the most related works close to our mechanism and that address cooperation between MAC and rout-

ing protocols.

In [1], we addressed an adaptive service differentiation based on buffer management and route establishment strategy. This proposal aims to find the best path according to application requirements in terms of delay. Each node periodically estimates the average transmission delay for each class of service. This information is injected into routing requests and replies crossing each node. The sender is then able to select the best path which fits its delay requirement. Furthermore, in order to overcome transit network characteristics due to new communications set up and mobility, we develop a new buffer management scheme for the audio class of service that aims to discriminate audio packets according to their tolerated end-to-end transfer delay and their current experienced delay.

In [10], the authors propose a mechanism for detecting network congestion. There are two metrics which are used to measure the congestion level. The first one, is the average MAC layer utilization around each node. Instantaneously, this metric can be equal to 1 or 0. It is equal to 1 if the MAC layer is utilized. The second metric, is the instantaneous interface queue length. The routing protocol looks to establish routes over no congested nodes. However, if we avoid busy nodes in route establishment, there are some routes that cannot be established even if they exist. At higher layer, these metrics can be used to decide or not data compression. When the medium is busy the sender can decide to compress the data. However, the compression should represent a trade-off between bandwidth consumption and the CPU time used for compression and decompression. In [11], MAC layer exploits the topology information collected by network layer to achieve fair channel scheduling and fix the problem related to hidden and exposed terminals. An enhanced backoff scheme is introduced. The authors suppose that a node has a knowledge of the whole network topology and so a proactive routing protocol should be used. Hence, it seems that for some scenarios, it is very hard, costly, and not efficient to address this cross-layer architecture regarding the dynamic traffic nature and the high mobile node speed. However, no information has been provided on how to compute the path per-formability index or other cross layer parameters. In [12], two cross-layer designs based on energy consumption are presented for wireless ad-hoc and sensor networks, namely ECPS and E2LA, which employ probabilistic dynamic programming (PDP) techniques and utilize cross-layer interactions between the network and MAC layers. They aim to enhance the operation of existing power-based multi-path routing protocols via cross-layer designs and optimal load assignments. Furthermore, the authors developed four distinct reward schemes for which E2LA assigns routing loads accordingly. In ECPS mechanism, the MAC sublayer provides the network layer with information pertaining to successfully receiving a CTS or an ACK frame, or failure to receive one. ECPS, in turn, chooses the route that will minimize the probability of error or, equivalently, maximize the expected reward.

The proposed medium access control (MAC)-based performance studies, revealed that battery capacity may not be efficient for achieving energy-based fairness and system longevity for wireless mobile multi-hop ad-hoc and sensor networks. However, energy conservation may be attained only if valuable MAC (and PHY) input is passed to the network layer.

Indeed, most of the proposals compute global or local metrics which are used to make decisions for route establishment, scheduling, tuning transmission rate, tuning power transmission, etc. However, in our work we investigate a new MAC layer adaptation scheme using both TXOP and CW parameters. The pre-

sented approach allows to select minimum forwarding nodes in the network while still adapting to local characteristics variations and maintain a good packet delivery.

3 Proposal description

3.1 Short overview

We propose a forwarding scheme and adaptive transmission opportunity in wireless ad hoc networks. The goal of our proposal is to achieve a good medium utilization while providing a good application performance. To this end, the routing layer selects as possible a minimum number of forwarding nodes (FN) to set up communications, in order to decrease the contention amount. Furthermore, FN functionality is balanced between nodes to achieve good resource management and fairness.

A critical issue in the selection of the proper broadcast and routing strategy in the ad hoc network is energy conservation and prolonging network lifetime while maintaining connectivity and satisfying latency constraints. We propose to consider both queue length fraction and battery to select FN. Each node includes these two metrics in hello messages. By this way, nodes are able to select the appropriate FN in a distributed way. Moreover, these accurate information allow nodes to manage their resource intelligently.

The number of flows that traverse a given node, indicate how much a node participate to the communications. Indeed, loaded nodes suffer from high queue drops and so rapid resource degradation when they cannot access to medium for a minimum duration. To overcome this problem, we adapt MAC layer parameters according to node traffic load. Thus, TXOP duration and CW setting are tuned according to an assigned weight that takes into account the node forwarding activities.

3.2 Multipath routing

As the energy conservation and the network lifetime is a critical issue in the wireless ad hoc network, we take the amount of energy left at neighbor nodes into consideration when selecting one route from multiple paths. The selected node is then chosen for all possible communication set up that have to traverse that hop, while its queue level does not reach 90% of its maximum level. To this end, each node needs to report its energy and queue levels to its neighbors. The current (residual) energy level is normalized to the maximum battery capacity and scaled to 100. The normalized residual energy level makes it easy to handle heterogeneous nodes with different battery capacity. An additional two bytes recording the energy and queue levels are piggybacked onto the hello messages. So, all the neighbors hear the packet and record the corresponding values. The multi-path selection thus takes all the next hops from available paths, and checks the associated normalized remaining energy levels known to the node. The next hop with the highest energy level is selected. Then, the other hop possibilities are classified according to their battery occupancy. When a FN does not still have the larger energy level or his queue occupancy reach the 90 %, the packet forwarding is balanced to the node of best quality in term of energy and queue occupancy. It is possible that the energy information collected at a node is not accurate. However, the promiscuous nature of wireless channel provides a node great opportunity of overhearing neighbor information, which enables a node maintaining almost-accurate records. The energy usage at a node indicates the amount of radio activities. Thus it can be regarded as an indication of traffic

load at the node. While selecting the next hop according to the energy levels, load balancing among the neighbors is achieved.

3.3 Selection Procedure of forwarding nodes

In order to minimize the complexity of QoS metric computation while maintaining an efficiency of the chosen metrics, each node has to compute periodically two parameters:

- **Normalized battery level:** The normalized battery level $E[E]$ is defined to be the ratio of the remaining energy RE to the maximum energy level ($MaxE$): $E[E] = \frac{RE}{MaxE} * 100$. To avoid frequent FN changes, we just consider absolute values. That is mean a node having 80.1 % or 80.5% of energy level values are considered 80 %.
- **Normalized queue occupancy:** The normalized buffer size ($E[B]$) is defined to be the ratio of the current buffer size (CB) to the maximum queue occupancy ($MaxB$): $E[B] = \frac{CB}{MaxB} * 100$

3.3.1 Computation of node weight

Each node can know the Forwarding Node List (FNL) in its hop by observing all received packets at MAC layer. Indeed, it looks if the destination and source addresses included in the packet header, are already recorded in the FNL or not. By this way, each node can have an accurate FNL. There might be another way that could be used to determine the FNL. The idea is to observe the RREP packets. However, this method can not be accurate since intermediate nodes can reply to RREQ messages. So, nodes toward destination could not have knowledge about this new communication set up.

The capture of packet addresses at MAC layer can give knowledge about the Traffic Fraction (TF) that a node is sending. These observations help each node in the same transmission range, to assign a weight w_i to each neighbor node i . We define $w_i = TF_i$ for all j in the neighbor list of i . When considering constant transmission rate, this parameter (w_i) can be expressed by the number of flows that traverse a given node i . In the latest case we can write: $w_i = \sum f_{ij}$, where j is the flow ID that traverse i .

3.4 Route establishment scheme

In this work, we extend AODV routing protocol to support our proposal [7]. When a source node tries to build up a path from itself to a certain destination, it generates a Route REQuest packet (RREQ). Besides those fields specified in AODV, it also sets the QoS indicators $E[E]$ and $E[B]$ parameters that we have defined above. Then, each node maintains for each reverse route this cost in the routing table entry. The routes are built based on the maximum energy. The route establishment can be done with different paths. Among the different next hop possibilities, we select the nodes that are recorded in FNL and have the largest weight. The nodes in FNL which have a queue level that exceed 90% of its maximum value are not chosen.

3.5 Role Rotation

Periodically, every node broadcast hello messages, which include its $E[E]$ and $E[B]$ parameters. A node compares its own values with its neighbors. If it is among the top richest nodes in its neighborhood, it may claim its ability to forward packets. So, it

updates its routing table. So, we allow the intermediate nodes to redirect the route on each hop and form cooperative coalitions on the fly.

All the other routing operations are the same as those in AODV to make the extended version compatible with AODV and, under different circumstance, the network may choose from original or extended AODV without any additional cost.

3.6 Adaptation of MAC layer parameters for active forwarding node

Many Results show the importance of considering the impact of MAC-layer parameter setting on the application performance [2]. We aim to provide better and efficient medium utilization for most loaded nodes while achieving a good QoS support and fair channel access.

3.6.1 Adaptive TXOP duration

We believe that differentiation based on adaptive packet bursting can provide a good performance in a distributed network where contention can be very costly. To get benefits from the $TXOP$ option, we propose that nodes in the network adopt an adaptive transmission opportunity duration based on the node congestion. Under some ergodicity assumption, the throughput of node i for one transmission can be expressed as: $th[i] = \frac{Psize[i]}{Tx[i]}$, where :

$$Tx[i] = CN * (IS[i] * ST + PktTx[i] + AIFS[i] + ST) + RTSTx + CTSTx + AIFS[i] + PktTx[i] + ACKTx + IS[i] * ST + 3 * SIFS + ST \quad (1)$$

is the average virtual transmission time of a packet by the MAC layer. $PktTx[i]$ is the transmission time over the wireless channel of a packet with size equal to $Psize[i]$, CN is the average number of collisions in a virtual transmission time (or a Virtual Transmission Cycle VTC), $IS[i]$ is the average number of idle slots resulting from the queue i's backoff for each contention period, $ACKTx$ is the acknowledgment's transmission time, and ST is the SlotTime which depends on the physical layer type. The above throughput expression 1 shows that the ideal case is reached when a successful packet transmission is followed by another successful packet transmission without any collisions or idle time loss, i.e. $CN = IS[i] = 0$. So, we can write:

$$Tx[i]_{(CN=0)}[i] = RTSTx + CTSTx + AIFS[i] + PktTx[i] + ACKTx + 3 * SIFS + S \quad (2)$$

The maximum throughput of node i is then:

$$max_th[i] = \frac{Psize[i]}{Tx[i]_{(CN=0)}} \quad (3)$$

We observe in Eq 3, that the throughput is still affected by the time elapsed to send RTS/ CTS packets. The CFB is introduced to send packets without using RTS/CTS frames as shown in expression 4:

$$TXOP_{dur}[i] = RTSTx + CTSTx + 2 * SIFS + (k_i + 1) * (PktTx[i] + ACKTx + 2 * SIFS) \quad (4)$$

Where k_i is the maximum number of packets that can be sent without using of RTS/CTS frames. In the basic EDCA scheme, $TXOP$ duration is initially fixed for all priority queues. This could not be efficient when node's traffic load and medium characteristics vary dynamically. In this paper, we aim to allow FN more medium access ability since they are almost very loaded. To this end, we consider the weight parameter w_i introduced above to tune the maximum CFB duration for each node during a VTC , so we can write:

$$TXOP_{dur}[i] = \frac{W_i}{\sum_{j=1}^{j=n} w_j} * VTC \quad (5)$$

where n is the neighbor number of i . From Eq 4, and Eq5 we can write:

$$VTC = \frac{\sum_{j=1}^{j=n} w_j}{W_i} * (Tx_{rts/cts} + k_i(Tx[i])) \quad (6)$$

To determine the value of VTC , we have just to fix the value of K_i packets that the most congested FN (that has the larger w_i) has to sent in order to avoid packet drops. Furthermore, we can set VTC as follows: $VTC = (\sum_{j=1}^{j=n} K_j Tx[j]) + backoff$, where n is the number of nodes in the same hop, and $backoff$ parameter is the average backoff value which is given by: $backoff = \frac{CW+2}{2}$

3.6.2 Contention Window max-min values and adaptive setting

In the previous QoS enhancement studies, contention window size was used as the main differentiation mechanism [5]. They consider the medium utilization and the amount of collision, the main parameter to enable differentiation and enhance the application performance. In our work, we follow another method that is based on the $TXOP$ duration value obtained by the above analysis for each neighbor node. So, if one node success to transmit packets, he adjust his CW_{min} as follow:

$$CW_{min}[i] = (\sum_{j \neq i} K_j * Tx[j]) / 2 + 1$$

The above formula is at the same time adaptive to the amount of communications because the $k_j * Tx[j]$ is dynamically settled according to traffic load of each node neighbors. Moreover, it can achieve differentiation because we allow more transmission opportunity duration for the most loaded nodes which leads to less CW_{min} . Hence, if we have node f which is most loaded. So $k_f * Tx[f]$ is the maximum of $k_j * Tx[j]$ for $j \neq f$. Then, for all neighbors n of f , with $n \neq f$, $CW_{min}[f] \leq CW_{min}[n]$.

Following the same reasons, we set the CW_{max} as follow:

$$CW_{max}[i] = (\sum_{j \neq i} K_i * Tx[j]) + 1.$$

4 Simulations and performance analysis

We implemented our proposal in ns-2 network simulator [6]. We have extended the AODV protocol and EDCA scheme to support our cross-layer algorithm. We report in this section the results of simulations. We also provide an analysis of performance obtained.

4.1 Scenario description

We simulated Local Area Network (LAN) and multihop network scenarios to show the performance of our approach. Our simulation uses video traffics to evaluate QoS support. Each active station, generates packets of size equal to 1280 bytes each 10 ms which corresponds to an overall sending rate of 1024 Kbit/s. To increase the load of the system, we increase the number of flows. Moreover, we consider an arbitrary starting and end time of communications to show how the proposed model could be adapted to the dynamic network load. The radio model is very similar to the first generation WaveLAN radios with nominal radio range of 250m.

In the following simulations, we assume that each wireless station operates at IEEE 802.11a PHY mode-6, see network parameters shown in Table 1.

SIFS	16 μ s
DIFS	34 μ s
TXOP	0.0015ms
CW _{min}	15
CW _{max}	31
Data rate	36 Mbits/s
Slot_time	9 μ s
CCA Time	3 μ s
Preamble Length	20 μ s
RxTxTurnaround Time	1 μ s
PLCP header Length	4 μ s

Table 1: IEEE 802.11a PHY/MAC parameters used in simulation

4.2 Performance metrics

To evaluate the performance of the different schemes, the following metrics are used:

- **Throughput** : This metric shows the total bytes that have been successfully delivered to the destination nodes.
- **Mean delay**: it is the average delay of all the flows. The average delay is used to evaluate how well the global delay performance of different flows.
- **Latency distribution**: latency distribution allows to trace the percentage of packets that have latency less than the maximum delay required by the applications. Real-time flows require both low average delay and bounded delay jitter.

4.3 Performance study in wireless LAN

We consider a simple scenario to show how performance is enhanced when considering the adaptive MAC Layer Parameters (AMP) that we proposed. The scenario consists of three nodes in the same transmission range of each other. The first and the second node send respectively 10 and 5 video flows to node 3. In Figure 1 and Figure 2 show the goodput and the delay distribution results. Indeed, AMP can provide significantly more 10% of total throughput compared to EDCA. Moreover, the coordinates (0.08, 80) and (0.08, 50) imply that 80% of packets have delay lower than 0.08ms. However, for the original EDCA scheme, only 50% have delay less than 0.08ms. The adaptive setting of CW values and $TXOP$ durations for all the flows reduce

the number of collisions that allows a good medium utilization. Hence, the throughput is improved and the delay is well minimized.

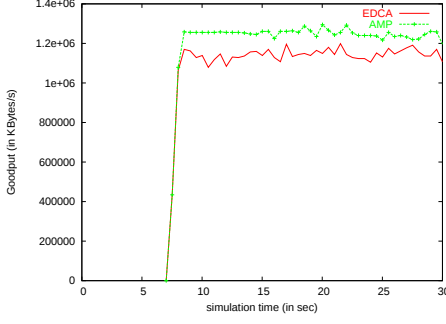


Figure 1: Goodput results

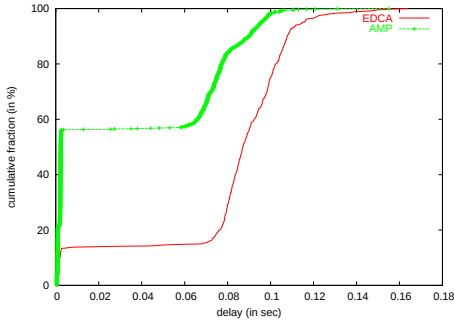


Figure 2: Delay distribution results

4.4 Performance study in wireless multihop Network

The simulated scenarios consists of 9 nodes located in a uniform distribution within an area of 1500x300 forming a multi-hop network. The nodes send video traffics to each other.

Figure 3 and Figure 4 show the throughput and the average delay performance, respectively for our proposed model and the basic protocol. We observe that CLFS provides significantly more total throughput compared to EDCA-AODV (Figure 3). There is more than 50% throughput gain when using the layer cooperation. This result demonstrates the benefits of reducing the FN number while adapting the MAC layer parameter to the traffic load. Indeed, as the load becomes heavier, the level of contention will not increase proportionally. By this way, the medium utilization is improved. Whereas for EDCA scheme, the high contention level affects the throughput performance due to the fact that its parameter setting is static and cannot be adaptive to the traffic load.

As we can see in Figure 4, at the beginning of simulation CLFS achieves higher delay than the basic approach. The tight between the two curves is minimized when all nodes start transmission. One reason behind this phenomenon is that, when routes are not yet exist, the selection of FN takes some delay before route establishment. However, this delay decreases over the time and achieve the same performance as EDCA-AODV protocols. This behavior could not affect the performance of our scheme since the delay tend to be improved once the selection of FN is done.

The main advantage of our proposal is that, it do not only enhance well the global throughput of the video applications, but

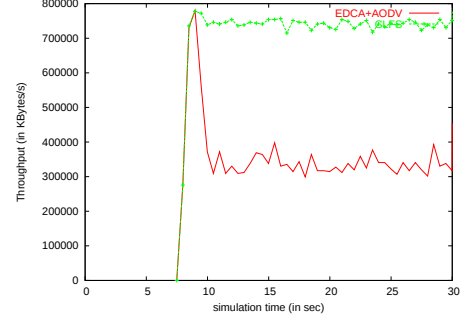


Figure 3: total throughput results

also can ensure a fair fairness degree among all the flows.

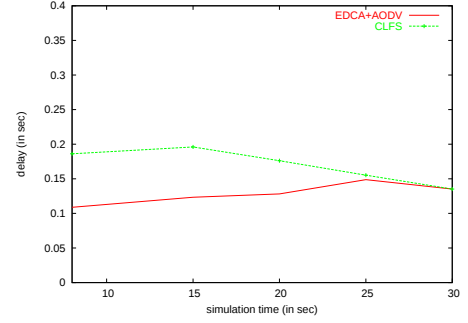


Figure 4: Average Delay results

Fairness Index (FI) is defined as: $FI = \frac{(\sum_{i=1}^n T_i)^2}{n \sum_{i=1}^n T_i^2}$, where n is the number of flows, and T_i is the throughput of flow i . We recall that $FI \leq 1$, and it is equal to 1 if all T_i are equal, which corresponds to the highest degree of fairness between the different users. As shown in Figure 5, our scheme is always fairer than EDCA-AODV basic protocols. The main reason comes from the fact that the AMP scheme adjust CW value regarding to the traffic load of neighbors which allow a fair medium access probability. Moreover, the adaptation of the $TXOP$ duration allocate to nodes relative medium occupation according to their load. This provides better fairness between different users since the queues of the different users will be transmitting almost all the time at the adaptive MAC parameters. This is not the case when using EDCA-AODV protocol because there is no consideration of node congestion which leads to an unfair medium access.

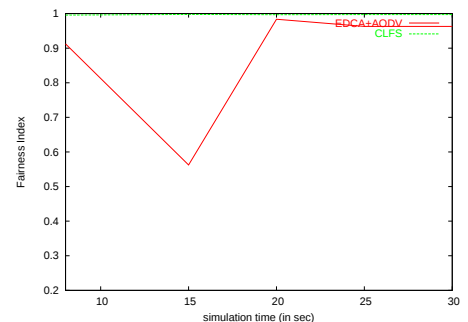


Figure 5: Fairness Index

5 Conclusion and Future work

This paper presented a cross-layer approach called CLFS, based on the cooperation between MAC and routing layers. Our proposal is mainly based on selecting minimum FN in the network considering their battery level and queue occupancy. On the other hand, it assigns adaptive MAC layer parameters to the nodes, which allows them to achieve high probability of transmission success. The simulation results we obtained show that our model provides a total throughput significantly higher than the basic scheme. Besides, it provides a higher degree of fairness than AODV-EDCA protocols between the different simulated flows.

Even though we implemented the model on AODV, the technique used is very generic and can be used with any on-demand protocol. Moreover, this proposal can be applied to single channel and multi-channel based medium access protocols, and there is no need for synchronization. We are working on the mobility effect on our proposal and we are going to provide, later on, a detailed analysis and remarks of the on-going results.

References

- [1] Lamia Romdhani and Christian Bonnet, "A Cross-Layer On-Demand Routing Protocol for Delay-Sensitive Applications", *PIMRC 2005*, Berlin, September 12-15.
- [2] Q. Ni, and al, "A Survey of QoS Enhancements for IEEE 802.11 Wireless LAN", *JWCMC*, John Wiley, vol.4, pp. 1-20, 2004.
- [3] IEEE 802.11e WG. Draft supplement to Part 11: "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: MAC Enhancements for Quality of Service (QoS), IEEE Std 802.11e/D9.0". August 2004.
- [4] IEEE 802.11. Standard 802.11: *Wireless LAN Medium Access Control (MAC) and Physical layer (PHY) Specifications*. 1999.
- [5] L. Romdhani, and al, "Adaptive EDCF: Enhanced Service Differentiation for IEEE 802.11 Wireless Ad Hoc Networks". *IEEE WCNC 03*, New Orleans, Louisiana, March 16-20, 2003.
- [6] Network Simulator-2. www.isi.edu/nsnam/ns/.
- [7] Perkins, Ad hoc on demand distance vector (AODV) routing, IETF, RFC 3561, Mai 2004.
- [8] E. Carlson, and al, "Performance Comparison of QoS Approaches for Ad Hoc Networks: 802.11e versus Distributed Resource Allocation", *Euro-pean Wireless*, Nicosia, Cyprus, April 10-13, 2005.
- [9] L. Romdhani and C. Bonnet, "Cross-layer's paradigm features in MANET: benefits and challenges", *PWC 2005*, Colmar, France, August 25-27, 2005.
- [10] Y. Hu and D. B. Johnson, "Exploiting Congestion Information in Network and Higher Layer Protocols in Multihop Wireless Ad Hoc Networks", *ICDCS*, Hachioji, Tokyo, Japan, March 24-26 2004.
- [11] M. Conti, and al. "Cross-Layering in Mobile Ad Hoc Network Design", *IEEE Computer Society*, February 2004.
- [12] A. Safwati, and al, "Optimal cross-layer designs for energy-efficient wireless ad hoc and sensor networks", *IPCCC*, 9-11 April 2003 Pages: 123 - 128