Self-organizing Mobile Ad Hoc Networks: Spontaneous Clustering at the MAC Layer

J. Alonso-Zárate[1], E. Kartsakli[2], P. Chatzimisios[3], L. Alonso[2], and Ch. Verikoukis[1]

[1] Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Av. del Canal Olímpic s/n, CTTC, 08860, Castelldefels, Barcelona, Spain
{jesus.alonso,cveri}@cttc.es

[2] Dept. of Signal Theory and Communications, Universitat Politècnica de Catalunya (EPSC-UPC)
Av. del Canal Olímpic s/n, EPSC, 08860, Castelldefels, Barcelona, Spain
{ellik,luisg}@tsc.upc.edu

[3] Dept. of Technology Management, University of Macedonia
GR-59200, Nousa, Greece
pchatzim@uom.gr

Abstract. We present in this paper a master-slave, self-organized, spontaneous, passive, and dynamic clustering algorithm embedded into the Medium Access Control (MAC) layer for Mobile Ad hoc Networks. Any mobile station gets access to the channel by executing a contention-based mechanism similar to the IEEE 802.11 Standard. However, once it seizes the channel, it establishes a temporary cluster to which closer neighbors can get synchronized. Within each cluster, any infrastructure-based MAC protocol can be executed. Link-level computer simulations have been carried out to show that this approach can remarkably improve the performance of ad hoc networks at the MAC layer.

Keywords: MAC, DQMAN, DQCA, Clustering, Ad hoc, Self-organizing.

1 Introduction

Mobile ad hoc networks (MANETs) offer a set of advantages that look very promising to suit some of the hard and challenging requirements of a great number of new applications, which range from low-cost commercial systems or in-home applications, to rescue operations [1]. The need for continued connectivity and spontaneous networking has turned mobile ad hoc networking into a hot research topic over the last years.

MANETs consist of a set of mobile stations that can freely move and want to communicate with each other. Since there is no central point of coordination, all the decisions should be made in a distributed manner and communications must be done by establishing peer-to-peer links between pairs of source and destination stations. In some cases, the source of information and its intended destination might not be within the same transmission range and, in this case,

F. Granelli et al. (Eds.): MOBILIGHT 2009, LNICST 13, pp. 242–253, 2009.

cooperation is a must. Stations might relay packets in a multi-hop fashion in order to establish end to end links through a variable number of hops. The management of this kind of spontaneous scenarios is very challenging and has attracted many researchers. The goal is to design efficient protocols that can bring to life all the potential advantages of ad hoc networking.

Regarding the unpredictable nature of ad hoc networks, the design of those protocols should take into account the dynamics of these systems. First, the capability of the terminals to freely move in the network makes difficult to consider a frozen topology. Second, the radio channel is time-varying and thus the connectivity of the network is hardly predictable. Third, the variety of stations and services with different data traffics, requirements of quality of services, and heterogeneous constraints in terms of delay and throughput, is growing day by day. In order to deal with such complex network architecture, next-generation protocols should be self-configurable and dynamically adaptable to the conditions of the environment or system.

On the other hand, and regarding the strict performance requirements posed by new applications, those protocols should also attain high-performance in highly dynamic environments. Unfortunately, the design of such protocols has been mainly focused on infrastructure-based scenarios.

Having these two concerns in mind, a novel self-configuring technique is presented in this paper to extend the use of high-performance medium access control (MAC) protocols to distributed mobile networks. The main idea is to integrate a dynamic clustering algorithm into the MAC layer to create a spontaneous, temporary, and dynamic virtual backbone wherein any infrastructure-based MAC protocol could be used.

The remainder of the paper is organized as follows. Section 2 is devoted to overview the concept of self-organization in mobile wireless networks. Clustering techniques as a means of self-organization are presented in Section 3. The concept of integrating a spontaneous clustering technique into the MAC layer is introduced in Section 4. A case study with the Distributed Queueing Collision Avoidance (DQCA) protocol [2] is also analyzed in this section. Finally, Section 5 concludes the paper and gives some final remarks.

2 Self-organizing a Mobile Wireless Network

The concept behind self-configuration is the capability of a system to detect changes in the local environment and react to them in order to either minimize or obtain the most of their potential consequences. Regarding communication networks, a more specific definition could be the one expressed in [3]; a system is self-organized if it is organized without any external or central dedicated control entity. Mobile stations may exchange local information in a peer-to-peer fashion to achieve an overall organization. Among other possibilities, stations might decide, in a distributed manner, to establish a virtual hierarchical structure in which some of them act as directors or coordinators for their local neighborhood.

Although the design of efficient techniques to self-organize a hardly predictable and mobile wireless network is not a trivial task, the potential benefits of self-organization make the effort worth it. Among these benefits we can emphasize the increase of the capacity and coverage range of the network by allowing relay communication, the reduction of planning and deployment costs, the flexibility and scalability of the network to add or remove terminals, and the robustness towards station failures.

The concept of self-organization is very heterogeneous and multidisciplinary. In [4], the concept of self-organization in cellular wireless networks is presented as a mechanism to minimize the costs of both network planning and deployment. As indicated by the ETSI (European Telecommunications Standards Institute), it is convenient to work on systems that avoid the need for frequency planning and make easier the addition or removal of any base station. This was, for example, one of the motivations for selecting Code Division Multiple Access (CDMA) as the air-interface for UMTS (Universal Mobile Telecommunications System), instead of the previously used Time Division Multiple Access (TDMA) in GSM. In [5], self-configuration mechanisms are used as a way to improve the scalability of hybrid networks by means of combining cellular and relay ad hoc wireless networks. Another approach of self-configuration is the IP address configuration. In the past, an administrator should provide each of the stations of a network with an IP address. With the DHCP (Dynamic Host Configuration Protocol), and, furthermore, with the development of a stateless auto-configurable IPv6 [6], this burden is avoided. The congestion control of the Transport Control Protocol (TCP) is another bite of self-configuration mechanisms that demonstrates the effectiveness and the scalability of decentralized systems.

In the field of MANETs, since the operation of each layer is tightly coupled with the other layers due to the high complexity and dynamism of such kind of networks, the self-configuring paradigm applies to the whole protocol stack at once. This means that the concept of self-configuration should be applied at the MAC layer, at the routing mechanisms, and at the network protocols in conjunction. This is the approach presented in this paper, where a spontaneous clustering mechanism is integrated into the MAC layer. Before getting into the details of the proposed self-organizing mechanism later in Section IV, the fundamental concepts of clustering are briefly overviewed in the next section.

3 Clustering: A Method for Self-organizing MANETs

Recently, experimental research has demonstrated that flat structures applied to MANETs perform well to a certain extent. When the size of a network grows in number of stations or in amount of traffic, the achievable performance in terms of throughput and delay is considerably reduced. However, by defining a hierarchical structure in which stations are classified into groups following certain rules, the management of the network can be made easier and the overall performance can be improved. This is the main motivation of clustering techniques by which the stations of a network get self-organized into groups or clusters.

Within a cluster, each station can play different roles depending on either its position or function. A station might be set to cluster head if it is the principal

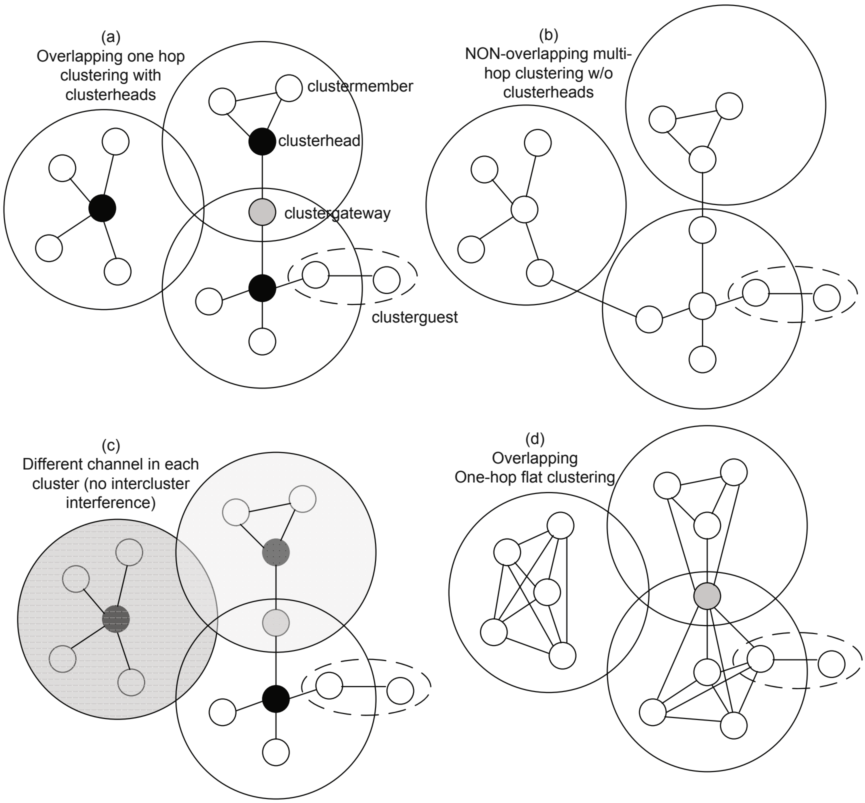

Fig. 1. Clustering Taxonomy

station in the cluster and it manages its one-hop neighborhood or to cluster member if it is connected to a cluster head. Furthermore, a station may act as a cluster gateway, if it is connected to more than one cluster head at the same time and, therefore, it is a potential relay for the inter-cluster communication, or as a cluster guest, if it is able to connect to a cluster member but not to a cluster head. This discussion is depicted in Figure 1.

One of the benefits of clustering is channel spatial reuse, which is strongly determined by the size of the clusters. Although small clusters can lead to a better spatial reuse, the end to end delay can be dramatically increased due to the potential occurrence of long paths, in terms of number of hops, between some pairs of stations. On the other hand, the use of big cluster sizes allows reducing these delays, but the spatial reuse is diminished and the interference range is increased. Therefore, a trade-off has to be managed when designing the size of the clusters, and thus the spatial reuse factor of the clustering scheme. In addition, typically the stations forming a MANET have a finite battery and thus the cluster-size must be properly selected. Big clusters imply higher transmission power, and therefore, higher power consumption. Moreover, as this power consumption does not grow linearly with the increase of the distance, the total energy cost of the transmission is also affected by the increase of the cluster size, which may be conveniently limited.

The set up and maintenance of a cluster topology may have a cost in terms of loss of the available resources, which may be caused by either *i)* the need for the explicit exchange of clustering information, *ii)* the time required to execute the clustering mechanisms, or *iii)* the costly process of re-clustering as the mobility of the network yields frequent changes in the topology and connectivity among the stations.

On the other hand, there is another trade-off between the benefits and drawbacks of applying some kind of cluster head centralization in a network; while the creation of a virtual backbone may be very useful for the overall network operation, cluster heads may become a bottleneck of the network, thus compromising its scalability.

Regarding the classification of clustering techniques, lots of clustering algorithms have been proposed in the literature and most of the strategies differ in the dynamic mechanisms to set up and maintain the cluster architecture. A survey on different clustering proposals can be found in [7] where authors classify them into six categories: dominating set-based clustering, low-maintenance clustering, mobility-aware clustering, energy-efficient clustering, load-balancing clustering, and combined-metrics-based clustering, depending on their criteria to define the cluster set. The main conclusion of that survey is that although different proposals are well suited for certain scenarios, it cannot be guaranteed that any of them is the best for all situations. Some examples of clustering schemes can be found in [8]-[13].

Taking into account this background, we present in this paper an approach to apply a spontaneous clustering mechanism at the MAC layer for networks without infrastructure.

4 Dynamic Clustering at the MAC Layer

4.1 Motivation

Traditionally, clustering algorithms have been based on the idea that the more stable the cluster set, the better the network will perform. The process of re-clustering a part of the network may entail a high cost in terms of resources due to the fact that one cluster head reassignment could trigger the re-configuration of the entire network. This could happen, for example, when the topology changes due to the mobility of the stations. This is known as the ripple effect of re-clustering and it has been traditionally avoided, especially in the case of large MANETs. However, when mobility is present, cluster stability is difficult to attain. In addition, if some stations are to be selected as cluster heads, it is difficult to design efficient criteria for selecting cluster heads in an extremely dynamic and changing environment as in the case of mobile wireless networks. As demonstrated in [14] the optimal cluster head set problem is NP-complete, and therefore, suboptimal clustering must be carried out in a highly dynamic environment.

Taking into account these considerations, and in order to extend the use of high-performance infrastructure-based MAC protocols to totally distributed networks, a dynamic clustering algorithm integrated into the MAC layer is presented in this paper. Up to our knowledge, the approach of integrating a spontaneous clustering mechanism into the MAC layer has never been tackled before in the literature.

Clusters are spontaneously created without explicit control information exchange whenever a station has data to transmit. The cluster structure is maintained for as long as there are data pending to be transmitted among all the stations associated to a cluster. Therefore, the cluster structure is spontaneously established and broken up according to the aggregate traffic load and the mobility of the network. Furthermore, cluster membership is soft-binding in the sense that there are no explicit association and disassociation processes, but a station belongs to a cluster as long as it simply receives the control packets broadcast by the master. Computer simulations discussed later in this section demonstrate that the performance of this spontaneous and dynamic mechanism outperforms legacy standard MAC protocols in mobile ad hoc networks by balancing a low-cost re-clustering mechanism with the benefits of employing a high-performance infrastructure-based MAC protocol in a distributed network. The clustering protocol is described in the next subsection.

4.2 Clustering Description

The proposed one-hop hierarchical clustering algorithm is based on a master-slave architecture wherein any station can operate in one of the following three modes; **master**, **slave**, or **idle**. Any station should be able to switch from one mode of operation to another one according to the dynamics of the network.

Despite the hierarchical cluster structure, all the communications can be done in a peer-to-peer fashion between any pair of source and destination stations. Note that the term destination in this context refers to the next-hop destination of a packet (which will be specified by the routing protocol), and not necessarily to its final destination station. For the description of the protocol, a slotted time scale is considered.

The mechanism works as follows. Any idle station with data to transmit listens to the channel for a deterministic period of time, as in [15], to determine whether the channel is idle or busy. If the channel is sensed idle, then the station attempts to establish a Master Service Set (MSS) by setting itself to master mode and starts broadcasting a clustering beacon (CB) every T_{frame} seconds. This transmission defines a MAC frame structure and allows neighboring stations to get synchronized with the master and become slaves. Slaves are responsible for transmitting an in-band busy tone (BT) upon the reception of each CB transmitted by the master. As long as any idle station willing to become master listens to the channel for at least T_{frame} seconds, these BTs ensure a minimum distance of three hops between masters and allow combating the hidden terminal

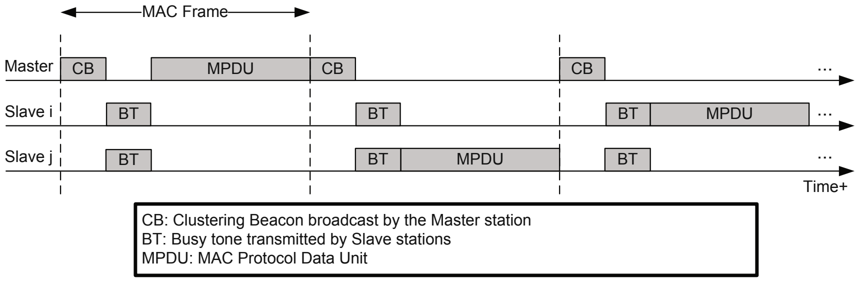

Fig. 2. Clustering Frame

problem. In addition, they constitute a collision detection mechanism for those stations which attempt to become master. The time elapsed between the BTs and the next CB is devoted to the exchange of data and control MAC Protocol Data Units (MPDU), wherein, indeed, any MAC protocol could be executed. This MAC frame structure is illustrated in Figure 2.

On the other hand, if an idle station senses the channel busy when attempting to establish a cluster, it initiates a Master Selection Phase (MSP) and sets its Master Selection Silent Interval (MSSI) counter to a random value within a MSSI window measured in time slots (as in the IEEE 802.11 Standard [15]). Likewise, any station performing a MSP listens to the channel and decrements the MSSI counter by one after each time slot as long as the channel is sensed idle. When the counter gets to zero, the station attempts to establish its cluster.

The value of the MSSI counter is determined as the sum of a deterministic period of time β and a randomized value selected within a constant-size contention window of length α. The purpose of the fixed period of time is to reduce the probability that a station becomes master twice consecutively in time, while the randomized time interval is required to reduce the probability of collision. It is worth mentioning that the size of the contention window should be properly selected as a function of the number of active stations in order to avoid either unnecessary wasted time in idle periods or a high probability of collision. A collision occurs when more than one station attempts to establish a MSS simultaneously. Any station which attempts to establish its MSS interprets that a collision with at least another station has occurred if no busy tones from slaves are received after the transmission of the CB. The stations involved in the collision reinitiate a new MSP by selecting a new value for their respective MSSI counters as soon as the collision is detected. Whenever a cluster is successfully established, its life time depends on the traffic load of the network. On the one hand, any station operating in master mode breaks its MSS and reverts to idle whenever there are no more pending data transmissions among all the stations associated to its MSS (including its data traffic). Whenever a slave mishears a number of CBs from the master, it reverts to idle mode. On the other hand,

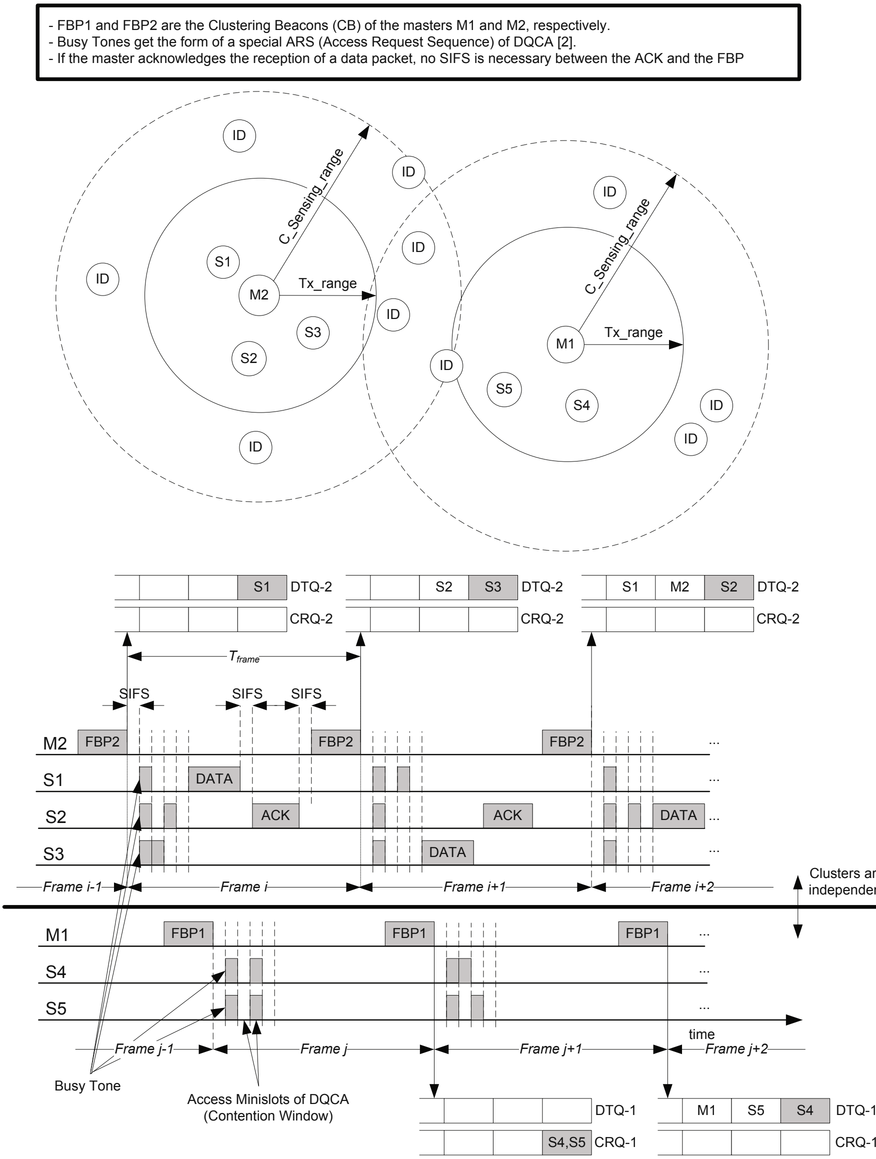

Fig. 3. Example: DQMAN Operation

and in order to avoid static cluster sets under heavy traffic conditions, any station operating in master mode also reverts to idle after a certain time, referred to as the Master Time Out (MTO), regardless of the pending data to transmit within its cluster.

4.3 Performance Evaluation

A performance evaluation of this spontaneous mechanism embedded into the MAC layer is presented in this section. In this case, it is considered that the high-performance DQCA MAC protocol [2] is executed within each cluster. The integration of the aforementioned dynamic clustering into the DQCA protocol is named Distributed Queueing MAC Protocol for Ad Hoc Networks (DQMAN). Masters act as access points and use the CB slot to transmit a Feedback Packet (FBP). An example of such a configuration is illustrated in Figure 3. Two stations, M1 and M2, have established their independent MSS (clusters). These stations periodically send the beacons FBP1 and FBP2, respectively, defining a time frame structure which allows stations S1 to S5 to get synchronized with their closest master. The time between beacons is used for the transmission of data where the MAC frame structure of DQCA is executed. This frame structure is divided into three parts:

1. A contention window further divided into access minislots wherein stations with data to send transmit an Access Request Sequence (ARS).
2. An almost collision-free data transmission part.
3. A control information part reserved for the transmission of ACK packets from any destination which receives a data packet and the FBP broadcast by the master. the FBP attaches feedback information on the state of each of the access minislots of the current frame. This is the only control information required by all the stations to execute the protocol rules described in [2].

Short Inter Frame Spaces (SIFS) are left after the transmission of either data or control information to tolerate non-negligible propagation delays and turn around times to switch from transmitting to receiving mode. Those stations operating in idle mode, labeled with ID in the figure, should wait until the cluster structure is modified due to the mobility of the network, the occurrence of an idle period

Table 1. System Parameters

Parameter	**Value**	**Parameter**	**Value**
Data packet length	1500 bytes	Message length	15000 bytes
Data Tx. Rate	54 Mbps	Control Tx. Rate	6 Mbps
MAC header	34 bytes	PHY preamble	96 μs
ACK length	14 bytes	SlotTime	10 μs
DQMAN			
FPB length	14 bytes	(α, β)	(32,10)
Access minislots	3	ARS	10 μs
MTO	100 (frames)	Busy Tones	10 μs
IEEE 802.11			
DIFS	50 μs	SIFS	10 μs
CW_{min}	32	CW_{max}	256
RTS length	20 bytes	CTS length	14 bytes

(no data packets pending to be transmitted within a MSS), or the execution of a MTO mechanism. In any of these cases, a reclustering process is triggered.

Link-level computer simulations in a custom-made C++ simulator have been performed to evaluate the performance of both DQMAN and the IEEE 802.11 Standard MAC protocol with both the basic and the collision avoidance access methods. A single-hop scenario has been considered and the emphasis has been put on calculating the saturation throughput of the two protocols as a function of the number of stations. The parameters used for the simulations are summarized in Table 1.

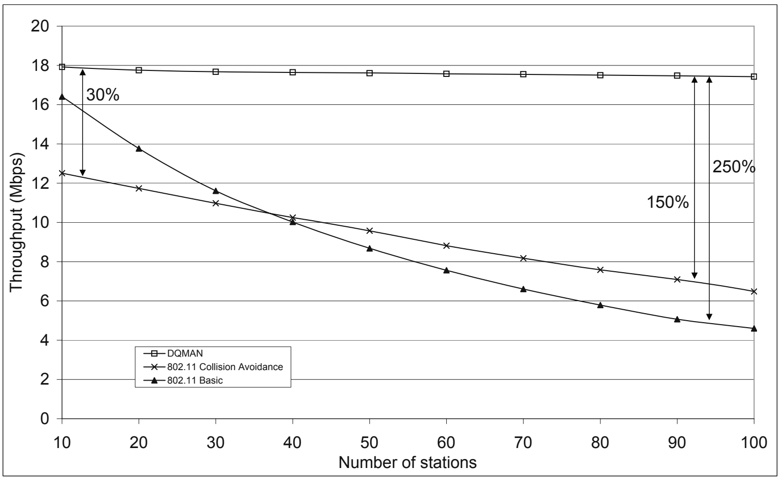

Fig. 4. Throughput Comparison (DQMAN vs. IEEE 802.11)

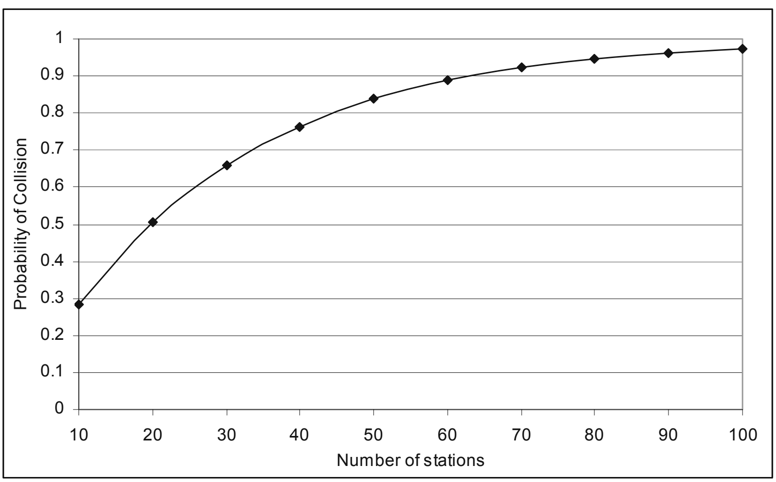

Fig. 5. Probability of Collision

4.4 Results

As illustrated in Figure 4, DQMAN outperforms IEEE 802.11 in all the considered scenarios. No only the saturation throughput is superior, but it is also more independent of the number of active stations. The saturation throughput of the IEEE 802.11 Standard drops dramatically as the number of active stations grows. For example, when 100 stations are considered, DQMAN attains 150% and 250% superior performance than the collision avoidance and basic access modes of the Standard, respectively. This is mainly due to the fact that the higher the number of stations, the higher the probability of collision. The probability of collision as a function of the number os stations is illustrated in Figure 5. Results show that the probability of collision can get close to 1 if the contention window size is not tuned dynamically. This is the reason why the 802.11 MAC protocol yields extremely poor performance for high number of stations. On the other hand, since the time devoted to contention in DQMAN is confined to clustering phases, a high probability of collision only causes a slight reduction of the saturation throughput. Therefore, the performance of DQMAN is less dependent of the configuration of the contention window.

In addition, it is worth noting that when the number of active stations is low, e.g. 10 stations, a minimum performance improvement of at least 30% and 16% in terms of throughput is still present due to the lower overhead of DQMAN compared to the IEEE 802.11 Standard in the collision avoidance and basic access modes, respectively.

5 Conclusions

The dynamic and spontaneous nature of MANETs poses hard challenges in their management and efficient operation. Since there is neither previous infrastructure nor any central point of coordination, all the decisions must be made in a distributed manner among the stations forming the network. Self-configuring techniques constitute a powerful tool to improve the performance and scalability of such kind of networks. The most common implementation of self-configuration in the field of MANETs is the use of clustering algorithms through which mobile stations get organized into groups or clusters.

We have presented in this paper the integration of a spontaneous and dynamic clustering algorithm into the MAC layer. Stations get access to the channel following a distributed contention-based access method. However, once they gain the control of the channel, they establish a temporary cluster structure where any infrastructure-based MAC protocol can be executed. Computer-based simulations show that the approach can enhance the performance of legacy 802.11 Standard networks up to 250%.

Acknowledgments. This work has been partially funded by the research projects NEWCOM++ (IST-216715), LOOP (FIT-330215-2007-8), PERSEO (TEC2006-10459/TCM), COOLNESS (218163-FP7-PEOPLE-2007-3-1-IAPP), R2D2 (CP6-013), and CENTENO (TEC2008-06817-C02-02).

References

1. Perkins, C.E.: Ad Hoc Networking. Addison-Wesley, Reading (2001)
2. Alonso-Zarate, J., Kartsakli, E., Cateura, A., Verikoukis, C., Alonso, L.: A Near-Optimum Cross-Layered Distributed Queuing Protocol for WLAN. IEEE Wireless Communications Magazine Special Issue on Medium Access Control Protocols for Wireless LANs 15(1), 48–55 (2008)
3. Prehofer, C., Bettstetter, C.: Self-Organization in Communication Networks: Principles and Design Paradigms. IEEE Communications Magazine 43(7), 78–85 (2005)
4. Spilling, A.G., Nix, A.R., Beach, M.A., Harrold, T.J.: Self-organization in future mobile communications. Electronics & Communications Engineering Journal, 133–147 (June 2000)
5. Dixit, S., Yanmaz, E., Tonguz, O.K.: On the design of Self-Organized Cellular Wireless Networks. IEEE Communications Magazine 43(7), 86–93 (2005)
6. Tobella, J.J.S., Stiemerling, M., Brunner, M.: Towards Self-Configuration of IPv6 Networks. In: IEEE Network Operations and Management Symposium 2004, vol. 1, pp. 895–896 (2004)
7. Yu, J.Y., Chong, P.H.J.: A Survey of Clustering Schemes for Mobile Ad Hoc Networks. IEEE Communications Surveys & Tutorials 7(1), 32–48 (First Quarter 2005)
8. Krishna, P., Vaidya, N.H., Chatterjee, M., Pradhan, H.K.: A Cluster-based Approach for Routing in Dynamic Networks. In: Proc. of the ACM SIGCOMM Computer Communication Review, pp. 49–65 (1997)
9. McDonald, A.B., Znati, T.F.: A Mobility-Based Framework for Adaptive Clustering in Wireless Ad Hoc Networks. IEEE Journal on Selected Areas in Communications 17(8), 1466–1487 (1999)
10. Haas, Z.J., Pearlman, M.: The zone routing protocol (ZRP) for Ad Hoc Networks, Internet Draft, Tech. Rep. (November 1997)
11. Ibriq, J., Mahgoub, I.: Cluster-Based Routing in Wireless Sensor Networks: Issues and Challenges. In: Proc. of the ACM Telecommunications, pp. 759–766 (2004)
12. Habetha, J., Wiegert, J.: Analytical and simulative performance evaluation of cluster-based multihop ad hoc networks. Journal of Parallel and Distributed Computing 63(2), 166–181 (2003)
13. Lin, C.R., Gerla, M.: Adaptive clustering for mobile wireless networks. IEEE Journal on Selected Areas in Communications 15(7), 1265–1275 (1997)
14. Li, C.: Clustering in Packet Radio Networks. In: Proc. of the IEEE International Conference on Communications (ICC 1985), pp. 283–287 (1985)
15. IEEE, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Std. 802.11-99 (August 1999)