Evaluating the Benefits and Feasibility of Coordinated Medium Access in MANETS

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ABSTRACT

Mobile ad hoc wireless network (MANETs) are characterized by a highly-dynamic topology where neither the duration of links between nodes nor their densities within the network can be foreseing. To better understand the effects of such issues in the medium access we provide a performance evaluation of two distinct MAC protocols. The first is our previously proposed HCT (Hybrid Contention/TDMA) Real-Time MAC protocol, which continuously adapts to topology modifications in order to provide a kind of coordinated medium access. Its performance is compared with a contention-based, non-coordinated CSMA protocol, which is the typical MAC protocol used in MANETs. We analyze both protocols with respect to their ability to deliver messages in a timely manner. More specifically, we compared the ratio of messages delivered within their deadlines and the medium utilization provided by these protocols. Such aspects where analyzed considering mobile networks with different spatial densities and speeds of nodes. This study also addresses the protocols overhead, especially for HCT-MAC. Obtained results show that HCT-MAC appears as a good solution for applications like search-and-rescue, autonomous highway driving (platooning), and multimedia, which require some kind of QoS guarantee in respect to the timely delivery of messages.

Categories and Subject Descriptors

C.2.2 [**Computer Systems Organization**]: Computer-Communication Networks—*network protocols*; C.4 [**Computer Systems Organization**]: Performance of Systems

General Terms

Performance,Experimentation

Keywords

Wireless Networks, MAC, MANETs, Real-Time Communication

1. INTRODUCTION

Analyzing some new-generation embedded applications one can see that they rely on mobile-connectivity. For instance, in the CarTel project [4] data is collected from sensors located on automobiles that move around the city. Modern Intelligent Transportation Systems use vehicle-to-vehicle (V2V) systems like platooning, which helps to reduce traffic congestions and provide safe driving [18]. The space community is developing distributed satellite systems (DSS) [2], where multiple mini-satellites in varying configurations are used to achieve a mission's goals collaboratively. Most of these applications require some kind of QoS guarantee in respect to the timely delivery of messages.

It happens that mobility causes topology changes and temporary link disruptions, affecting communications predictability. So the challenge in this context is how to rely on wireless links to achieve timing guarantees. This issue presents a kind of contradiction in the real-time domain, as it conflicts with the need for temporal determinism. This allows us to conclude that a suitable MAC for such scenario would be the one that can prompt react to topology changes, so that the effects of mobility are minimized.

Several MAC protocols where designed to be used in ad hoc networks, but most of them did not take into account mobility issues, as contantion-based medium access has been the typical solution to deal with mobility. In [9], Kumar et al presented a survey about MAC protocols used in ad hoc wireless networks. The well known Z-MAC [13], for instance, is a dynamic protocol that adapts itself to the network conditions, using CSMA during normal workload and TDMA in high workload. Its drawback comes from the high overhead for reconfigurations (about 30s according to authors), which makes it not suitable for mobile applications. Another example is the AdHoc-MAC [1], which was conceived for inter-vehicles communication using a distributed TDMA slot allocation mechanism named RR-ALOHA. Its drawback comes from the need of configuring the application offline, making it not applicable for mobile applications.

Despite the limitations of such protocols, it is possible to observe that hybrid approaches to medium access control are the key to achieve timely behavior in mobile networks. Inspired on that we proposed the so-called Hybrid Contention/TDMA-based (HCT) MAC [14], which aims to provide a time bounded medium access control for mobile nodes that communicate through an ad hoc wireless network. The key issue in this protocol is to self-organize the network in groups of adjacent nodes called *clusters*, as a mean to solve the problem of timely transmission of messages. It assumes a periodic message model and a transmission cycle divided in time-slots, where each cluster reserves a predefined number of time-slots that can be assigned to its member nodes.

The current paper presents the recent advances in HCT-MAC design and discusses results obtained from an intensive simulation study related to its application in MANETs applications that rely on timely delivery of messages. Its goal is to emphasize the benefits of having coordinated medium access to achieve the timing requirements when compared to the traditionaly used contention-based approach (CSMA).

In the simulations we compare the ratio of messages delivered within their deadlines and the medium utilization presented by HCT-MAC and CSMA protocols, considering networks with different spatial densities and speeds of nodes. We also present some hints on the existing performance bounds of the protocols. To conclude, our study analyzes the feasibility of using an adaptive protocol like HCT-MAC in respect to its overhead.

The remainder of the paper is structured as follows. Section 2 discusses the main related works. Section 3 provides an overview of our HCT-MAC protocol. Section 4 details the performance metrics to be analyzed in our evaluation. Section 5 presents the simulation experiments and discusses the obtained results. Finally, section 6 concludes the paper.

2. RELATED WORKS

The great majority of research works concerning MAC protocols for MANETs tackle the use of contention-based protocols [9]. Indeed, these protocols easily adapt to topology changes, since no agreement between nodes is required prior to transmissions. That is the case of CSMA/CA protocols, like the variations implemented in the standards IEEE 802.11 [7] and IEEE 802.15.4 [6].

However, despite their adaptability to topology changes, they are not predictable regarding medium access delay, so cannot guaranty a timely delivery of messages. This happens mostly due to collisions and inherent random backoffs. For this reason we investigated other MAC protocols that address the timely delivery of messages using ad hoc networks. But, on the other hand, few of them were designed taking mobility issues into consideration.

Some contention-based MAC protocols include prioritization mechanisms, which could be used to implement a scheduling policy. For instance, the Black Burst is a MAC protocol which employs a preamble with variable length to prioritize messages, but it does not adapt to frequent changes in topology [16]. The WiDom is another contention-based MAC protocol, which adapts the dominance protocol used in the CAN bus to a wireless channel, implementing static-priority scheduling with a large number of priority levels [11], but it was designed to networks with static topologies. In the case of the IEEE 802.11 standard, the different IFS (Inter Frame Space) and initial contention windows defined in the access categories of EDCA, a statistically prioritized version of its CSMA/CA MAC protocol, can only provide a coarse-grained prioritization with few priority levels and do not avoid collisions [5].

Another set of MAC protocols called hybrid combine contention and resource-reservation to perform medium access. The Z-MAC [13] defines a TDMA transmission cycle where each node can allocate one time-slot and use it to transmit messages in a contention-free manner. It also allows nodes to use other nodes time-slots, but using CSMA with lower priority. Z-MAC was designed for wireless sensor networks with static topologies, so its main drawback in mobile networks resides in the delay it can suffer when nodes need to allocate time-slots, since it employs a distributed consensus protocol.

The IEEE 802.15.4 standard also includes a hybrid operation mode, using contention-based medium access with CSMA/CA and contention-free medium access with GTS (Guaranteed Time Slots). In that mode, groups of nodes are formed to share a superframe, which is a cyclic interval of time when member nodes can receive and transmit messages. Superframes are started by a control frame called beacon, that must be transmitted by the group coordinator. The standard does not define how the group coordinators must schedule their superframes (i.e., how to schedule beacon transmissions), such that the superframes of different groups of nodes do not overlap. In [8] it was proposed a beacon scheduling algorithm for networks with cluster-tree topologies. Proposals for mesh topologies where presented in [3] and [10], however they considered only networks with static topologies. Thereby we conclude that existing hybrid MAC protocols do not cope with dynamic topologies, and thus are not suitable for mobile networks.

3. THE HCT-MAC PROTOCOL

The Hybrid Contention/TDMA-based (HCT) MAC was designed to provide time bounded medium access control for nodes that communicate through a mobile ad hoc wireless network (MANET). While the first ideas around this protocol where presented in [14], the protocol has been improved over the last years. This section details the core concepts and the most recent aspects related with HCT protocol.

3.1 Adopted Network Model

It is assumed a network model where mobile nodes communicate through a MANET. Nodes move continuously according to some mobility model, leading to the creation and extinction of data links among them. Transmissions are performed in broadcast and there are no acknowledgements in the MAC layer. Nodes exchange both data and control messages in a periodic manner. We assume a pessimistic scenario, which means that nodes can transmit data messages at the same time.

Control message periods (or transmission cycles) are static and defined offline. This way, within the neighborhood of each node, there is a limit in the amount of messages that can be transmitted without collisions within a transmission cycle. This suggests that designer should take a closer look into the application ir order to properly parameterize the protocol.

Since in MANETs the topology changes frequently, it is not possible to guarantee that a node can always transmit one message at each cycle. This can be related to the density of nodes, defined by the number of nodes whose transmissions can collide at a given location in the network. If that density exceeds the limit of messages per cycle, some nodes will not be able to transmit their messages. Besides that, in the adopted network model nodes perform an opportunistic resource-reservation, such that they can obtain a temporary throughput guarantee. Since network topology is dynamic, such resource-reservation must adapt to solve conflicts that can arise when neighborhoods of nodes change.

3.2 Protocol Overview

A key issue in HCT design is how to self-organize the network nodes to coordinate transmissions. The adopted solution consists in creating dynamic groups of adjacent nodes called *clusters*, as discussed in [14]. It assumes that wireless links within groups of nodes can last enough to allow the

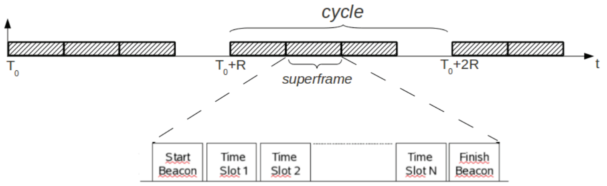


Figure 1: Timing in HCT: cycles of length R divided in superframes

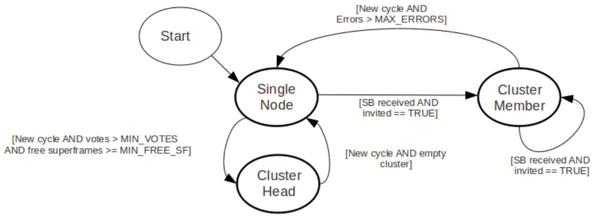


Figure 2: Clustering in HCT-MAC

Table 1: Evaluation Metrics

Metric	Description
Rate of received frames	Ratio between received frames and number of time-slots
Rate of delivered frames	Ratio between successful delivered frames and transmitted frames
Clusterized rate	Ratio between clusterized cycles and total cycles
Disconnected time	The interval of time a node is expected to wait to enter a new cluster

use of a resource-reservation approach among clusters.

The HCT-MAC is a hybrid protocol because it has both contention-based and resource-reservation characteristics. It accesses the medium with contention is performed in a CSMA-like manner and resource-reservation is implemented similarly to a TDMA. Initially all nodes operate in contention-based mode and, as they succeed to form clusters, they might operate in resource-reservation mode.

In HCT time is organized using a periodic and hierarchical structure, as illustrated in figure 1. A *cycle* is the basic period for transmissions, thus it works like a time unit for the protocol (it is an interval of time that is common to all clusters). Cycles are divided in *superframes* that are allocated by clusters. Finally, superframes are subdivided in *time-slots*, which can be used by nodes for message transmissions. Superframes are delimited by two control frames called *start beacon* and *finish beacon*. Transmission cycle length is a key parameter in HCT-MAC. It limits the number of superframes per cycle and, consequently, the number of available clusters.

The TDMA component of the HCT depends on the clustering of the nodes, which must be performed in a self-organized manner. Self-organization is a requirement because the HCT protocol was designed to be used in mobile ad hoc networks, where nodes are not previously aware of the topology, neither of their neighborhoods. The protocol assumes that each node performs initially a contention-based medium access and, as they become a cluster member, they switch to reservation mode. In other words, as nodes self-organize in clusters they can reserve bandwidth and transmit messages in a timely manner. More information about this procedure can be obtained in [15].

In HCT-MAC clusters represent sets of nodes that agree to share a superframe, which represents a portion of the network bandwidth. It must be noted that a node can send messages to any other node within its range, since clustering has the single purpose of helping nodes to allocate time-slots within a superframe. A key element in the cluster topology is the cluster-head, a special node responsible to start cluster transmissions with a start beacon, to account for idle and used time-slots, and to report successful transmissions within a finish beacon sent in the end of a superframe. Ideally, the cluster-head should be the node with the best link qualities to adjacent nodes within the region to be covered by the cluster, in order to minimize the probability of transmissions errors in the scope of the cluster.

The clustering procedure is driven by two main guidelines: i) single nodes elect the best nodes to become cluster-heads and ii) cluster-heads choose and invite the best nodes to become cluster members. Figure 2 shows how nodes change their roles between cluster-head, member node and single node. According to that, each node starts as single node, and can change to member node if an invitation is included in the start beacon received from a cluster-head. It becomes again single node if it received a start beacon which does not include an invitation, or if it does not receive a start beacon within one transmission cycle. To become cluster-head, a single node must receive enough votes from its neighbours. Finally, a cluster-head becomes single node if its cluster is empty. Clustering is performed continuously, such that HCT can adapt to topology changes which affect links qualities between nodes.

4. EVALUATION METRICS

This section presents and discusses the set of metrics used in our experiments, summarized in table 1. The main goal of the experiments were to analyze the benefits of using a hybrid protocol like HCT to provide timely delivery of messages and also to achieve better medium utilization. Another target of the experiments was to evaluate the feasibility of using HCT, i.e., to estimate the overhead of its coordination mechanisms.

Timely delivery of messages is implicit in HCT, i.e., if messages arrive the destination they are within the deadline. This is due to the TDMA component of HCT.

Medium utilization is a prominent result of a MAC protocol, because it informs how much of the channel capacity can be effectively used. A MAC which presents a given probability of transmission errors due to collisions cannot fully utilize the channel capacity. Moreover, in this case some messages are expected to be lost due to collisions. In fact, contention-based MACs, like the well known CSMA/CA [6, 5] and its variations, perform a probabilistic medium access and commonly use random delays before transmitting messages to reduce the probability of collisions. However, a MAC that employs some kind of coordination among transmissions of different nodes, like our proposed HCT-MAC, can improve the medium utilization. In this case, channel can be better utilized if collisions are very unlikely and random delays become unneeded.

The performance of HCT with respect to medium utilization was investigated by two metrics called i) *rate of received frames* and ii) *rate of delivered frames*. The first metric gives the ratio between the number of received frames and the maximum allowed according to TDMA. The second metric refines the former metric by accounting for the successful delivered frames, which were received by nodes for whom they were addressed. When combined, these metrics can estimate how close of TDMA performance HCT was. scenario defined by spatial density of the network and mobility pattern.

HCT performance in respect to medium utilization is expected to lie between a pure contention-based MAC like CSMA and a pure TDMA MAC. In case of TDMA and assuming a frame fills one time-slot entirely, if a transmission cycle T has N time-slots, a node can receive at most $N-1$ frames per cycle. In a CSMA MAC, nodes contend for the medium and thus their transmissions are subject to collisions. If nodes transmit frames with period T using CSMA, the number of frames each node receives is expected to be smaller than $N-1$ due to collisions. Since HCT combines both medium access modes, the amount of frames each node receives should be upper bounded by TDMA and lower bounded by CSMA.

The expected enhancement in medium utilization and timely delivery of messages that can be provided by HCT depend on the feasibility of its resource-reservation mechanisms. The resource-reservation access mode of HCT depends on the network self-organization in clusters, which occurs continually. Nodes form a cluster when some node is elected as cluster-head and invites other nodes to use the time-slots which are available to the cluster, as explained in section 3. *Both election of cluster-head and invitation of cluster members are driven by the measured link quality estimation performed by each node, in such way a cluster can be composed by nodes with good relative links qualities. In a mobile network, links qualities change over time due to nodes movements, which implies clusters being modified or dissolved, and new clusters being formed. This way, each node can alternate intervals of time when it is member of cluster and when it waits to enter a new cluster.*

In order to evaluate such feasibility, two metrics where defined: *clusterized rate* and emphdisconnected time. The metric *clusterized rate* represents the average ratio of the number of clusterized cycles experienced by each node and the total number of transmission cycles. Since there is a limit in the number of possible clusters within 2 hops, the *clusterized rate* is expected to depend both on the network size and spatial density. Moreover, mobility can make clusterized intervals shorter.

The so-called *disconnected time* represents the interval of time a node is expected to wait to enter a new cluster. This comes from the fact that mobility implies changes in clusters memberships, what means that a clusterized node can leave its cluster (or even its cluster can be dissolved) and wait some time until entering a new cluster. Once outside a cluster a node cannot benefit from the contention-free medium access provided by HCT. The *disconnected time* is calculated as a cumulated probability density function which gives the probability that a node suffers a given delay to enter a new cluster.

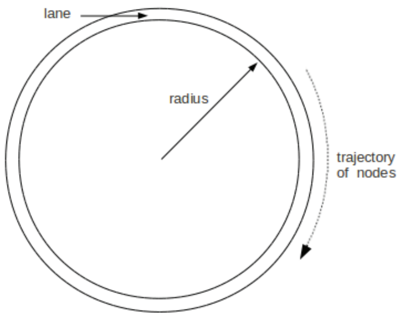


Figure 3: Mobility model: nodes move following a circular trajectory

5. SIMULATION EXPERIMENTS

This section presents a simulation study developed in order to provide a clear understanding on the ability of HCT-MAC protocol to fully utilize the medium and deliver frames within their deadlines in networks with mobile nodes, compared to a traditional CSMA protocol. It also investigated to which extent HCT was able to clusterize nodes in the simulated scenarios, which relates to the feasibility of its resource-reservation mechanisms.

Simulations were performed using the Omnet++ framework [17]. HCT model used as physical layer the radio and wireless channel models from project Castalia, maintained by the National ICT at the University of Australia [12]. They implement the signal model proposed in [19] and simulated a IEEE 802.15.4 compatible radio. These models were modified by us to support mobility.

In our simulations we used a sort of circular mobility model. Nodes moved along the 10 m width circular track (see figure 3) with variable radius. Groups of 40 to 60 nodes were disposed randomly along the circular track, moving in the same direction with speeds between 0 and 40 m/s, with a 2 m/s step. Once started a simulation, the speeds of nodes did not change. The track radius ranged from 10 up to 150 m, in the case of networks with 40 nodes, and 30 up to 300 m in networks with 60 nodes, both using steps of 10 m.

The spatial densities of the networks were calculated by the ratio between that enclosed area and the number of nodes, and was expressed as the average distance between nodes. This way it was possible to vary the spatial density of the networks and their degree of mobility. The physical layer parameters were chosen to simulate an indoor environment with no obstacles between nodes, and typical transmission range of 150 m. Table 2 summarizes the simulation parameters.

In respect to the network load, each node in the simulation periodically sent a message addressed to the neighbour which presented the best link quality in the previous transmission cycle. The resulting workload was balanced such that all nodes sent and received (in average) the same amount of messages.

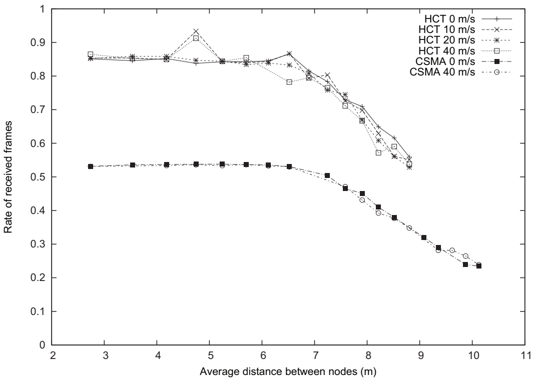
HCT specific parameters are summarized in table 3. Each transmission cycle in HCT had 6 superframes with 8 time-slots each, with time-slots length of 1 ms. It allowed clusters with at most 7 nodes, as 2 time-slots are reserved for Start and Finish Beacons, but cluster-heads used Start Beacons to encapsulate their data messages. One superframe was

Table 2: General Simulation Parameters

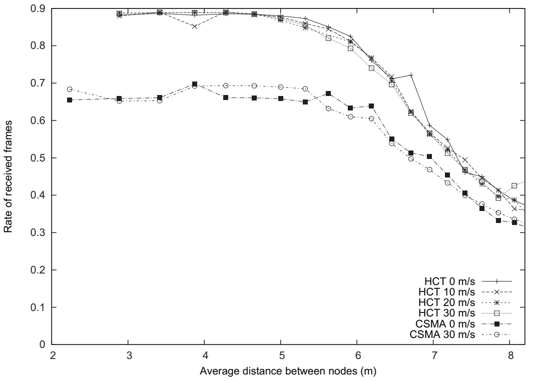
Simulation Parameter	Value
Period of messages	48 ms
Deadline	96 ms
Maximum hops	1
Message length	16 bytes
Simulation Time	120 seconds
Mobility Model	Race (circle)
Circle Radius	from 10 upto 300 meters
Speed	from 0 upto 40 m/s
Number of Nodes	40 and 60
Sensitivity	-95 dBm
Default Transmission Power	-5 dBm
Thermal Noise	-100 dBm
Path loss exponent	2.4
Path loss at d0	55 dBm
d0	10 m

Table 3: HCT Simulation Parameters

Simulation Parameter	Value
Cycle length	48 ms
Time-slot	1 ms
Superframe size	8 time-slots
Number of superframes	6



(a) Network with 40 nodes



(b) Network with 60 nodes

Figure 4: Rate of received frames

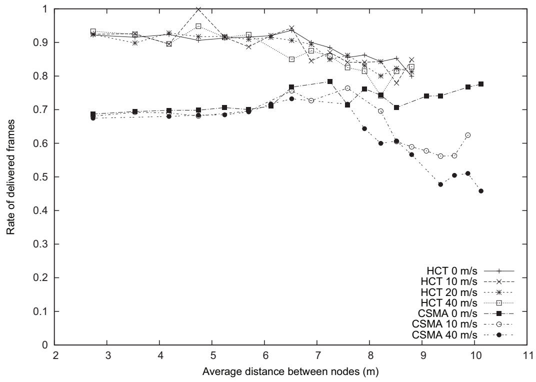
reserved for contention-based access, to be used by single nodes. In that case, such nodes contended for the medium only within unallocated superframes.

5.1 Analysis on Performance and Medium Utilization

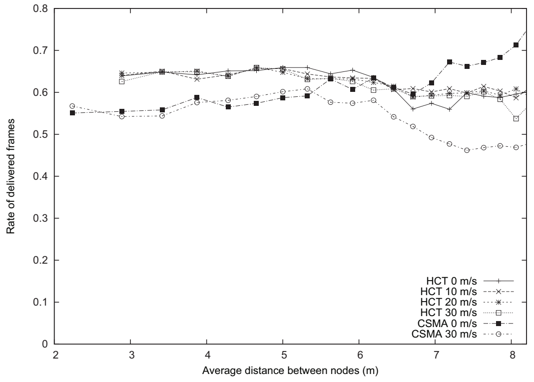
The *rate of received frames* obtained for HCT with particular maximum speeds of nodes had a low variability, considering networks with 40 and 60 nodes. In both cases, the *rate of received frames* presented similar results with different speeds (from $0 m/s$ to $30 m/s$) as shown in figures 4(a) and 4(b). It must be noted that in these experiments the transmission cycle of HCT would allow at most 35 nodes in resource-reservation mode in every location of the network (i.e. 5 clusters with at most 7 nodes each, since one superframe was reserved to contention-based access). Therefore, in networks with 40 nodes almost every node could clusterize and operate in resource-reservation mode, even in higher spatial densities. However, in networks with 60 nodes this was not true unless the spatial density corresponded to neighborhood sizes around 35 nodes. It can be clearly seen that HCT outperformed CSMA as spatial density increased (i.e. as average distance between nodes decreased). In this case, as nodes got closer their neighborhood sizes increased, leading to a higher probability of collisions in CSMA. Since HCT organizes as many nodes as possible in clusters to perform a short-range resource reservation, these clusterized nodes could transmit without incurring in collisions. The curves also show that CSMA performance approached HCT as spatial density decreased. This can be related to the smaller resulting neighborhood sizes, which resulted in lower probability of collisions if CSMA was used. Finally, since CSMA does not perform any resource-reservation nor self-organization, it must be little affected by speeds of nodes as confirmed in the plots. A similar result was obtained for the *rate of delivered frames*, which accounts for the received frames which were actually addressed to receiving nodes.

Rate of delivered frames relates the amount of delivered frames with the number of data frames generated over the network. As shown in figure 5(a), HCT presented a significantly higher *rate of delivered frames* than CSMA in networks with 40 nodes, when higher spatial densities were considered. The variability of this *rate of delivered frames* did not present a significant dependence to speeds of nodes in the case of HCT, but with CSMA the results for lower spatial densities were better with lower speeds. In networks with 60 nodes, shown in figure 5(b), HCT still outperformed CSMA in higher spatial densities but with a smaller difference.

Obtained results regarding *rate of received frames* and *rate of delivered frames* showed that HCT presented a better medium utilization than CSMA. It also showed that in some scenarios HCT approached the performance that a TDMA MAC would provide with respect to medium utilization. The better performance of HCT can be related to its resource-reservation access mode, which allows node to



(a) Network with 40 nodes



(b) Network with 60 nodes

Figure 5: Delivered messages

obtain exclusive access to the medium in a contention-free manner.

5.2 Analysis on Network Self-organization

Since the self-organization capability of HCT is the key to its resource-reservation mode, in this section it is investigated the self-organization of the simulated networks. In other words, it was evaluated the suitability of HCT to deal with mobility issues. Therefore it was measured the number of cycles nodes where able to stay clusterized in the different scenarios, and also how long nodes had to wait in order to enter a new cluster.

The *clusterized rate* was calculated for each simulation run of networks with 40 and 60 nodes, as shown in figure 6. It can be seen that in networks with 40 nodes the *clusterized rate* was quite steady and did not vary significantly with speed. In this case, most of nodes could clusterize since at most 5 clusters within 2 hops, with 7 nodes each, can be formed. This way, even in scenarios with high spatial densities almost all nodes were clusterized. But in networks with 60 nodes a proportionally smaller number of nodes could clusterize in high spatial densities. The *clusterized rate* in those networks remained steady in denser scenarios, and increased as the spatial density decreased enough to allow more clusters to be formed (but restricted to the defined limit within 2 hops around each cluster).

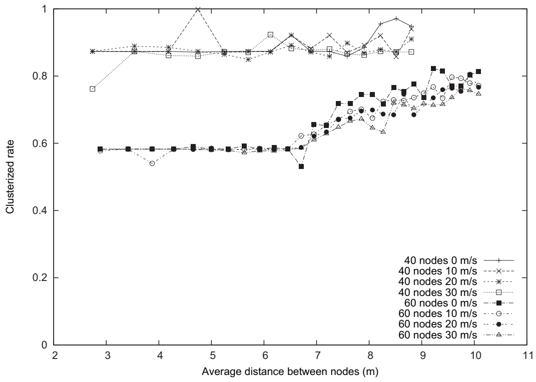


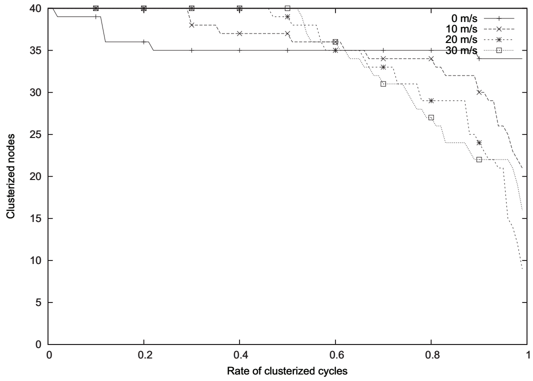
Figure 6: Clusterized rate

The *clusterized nodes* gives the number of nodes which presented at least a given number of clusterized cycles. It was calculated considering networks where the spatial density allowed a high *clusterized rate*. In networks with 40 nodes and average distance of $7.8m$ between nodes, shown in figure 7(a), the *clusterized nodes* had a clear dependence with speed. The figure shows that there was a threshold in the *clusterized rate* above which *clusterized nodes* suddenly and steadily decreased. Despite that, many nodes could stay clusterized almost all the time. When networks with 60 and average distance of 10 m between nodes were considered, the threshold in the *clusterized rate* appeared earlier and the steepness of *clusterized nodes* decay was more intense. In fact, in networks with 60 nodes few nodes were able to stay clusterized all the time. If *clusterized rate* and *clusterized nodes* reflects how many of the total transmission cycles correspond in average to clusterized cycles, it lacks the information about how long a node is expected to wait before becoming a cluster member.

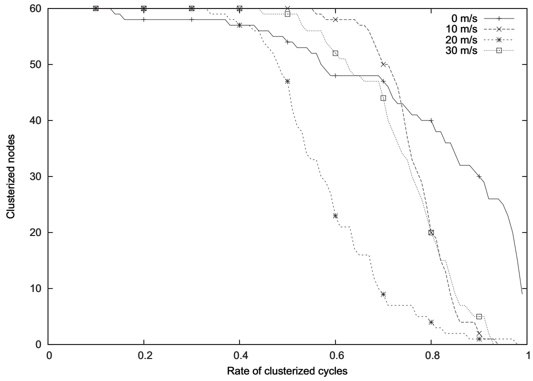
In the case of networks with 40 nodes, it can be expected a short *disconnected time*, since almost everyl node was clusterized during the simulations, as shown in figure 8(a). It corresponds to a scenario where nodes were distant each other $4.7m$ in average, and the network had a high *clusterized rate*. It can be seen that once a mobile node left a cluster, it was very likely that it entered a new cluster within $200ms$ (which corresponded to about 4 transmission cycles in the experiments). In networks with 60 nodes, with average distance of $10m$ between nodes which resulted in a reasonable *clusterized rate*, it can be expected a longer *disconnected time* as shown in figure 8(b).

6. CONCLUSIONS

This paper concerned the medium access issues in MANETs applications that rely on timely delivery of messages. It presented and discussed results obtained from an intensive simulation study that investigated the use of our previously developed coordinated MAC protocol named HCT-MAC.

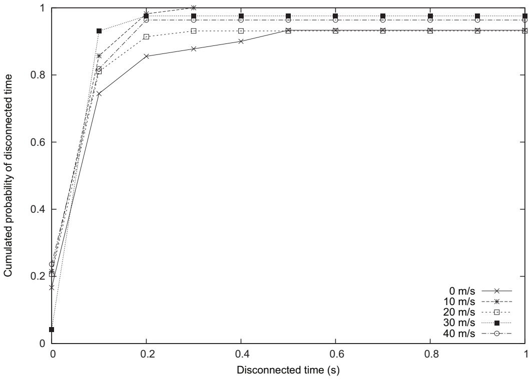


(a) Network with 40 nodes

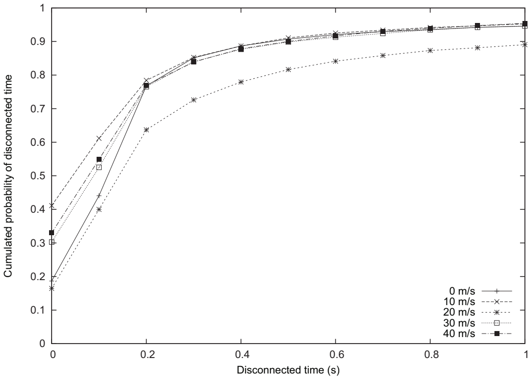


(b) Network with 60 nodes

Figure 7: Nodes with at least a given clusterized rate



(a) Network with 40 nodes



(b) Network with 60 nodes

Figure 8: Disconnected time

More specifically, the study investigated at which extent the HCT MAC protocol would improve the medium utilization and timely delivery of messages in scenarios with highly mobility of nodes. Performance comparisons against the tradiciontaly used CSMA protocol were provided, as this protocol is a *de facto* solution for medium access in MANETs.

Simulation results showed that HCT outperformed CSMA in scenarios with different network sizes, spatial densities, and speeds of nodes. Despite its overhead due to network self-organization and control frames, HCT still presented a higher medium utilization and rate of successfully delivered messages compared to CSMA. Moreover, in scenarios where HCT was able to keep almost the whole network self-organized, it approached the performance it would be expected from a TDMA-like MAC protocol. However, in networks with large spatial densities its performance was similar to CSMA.

The better performance on medium utilization and timely delivery of messages of HCT can be related to its resource-reservation access mode. That was analysed on the experiments on network self-organization, which gave the ratio of nodes which were able to clusterize and thus to operate in resource-reservation mode. These results showed that the ratio of clusterized cycles each node experienced during the experiments was related to the spatial distribution of nodes in the experiemnts, but there was no clear dependence on speeds of nodes. However, speeds influenced the time that nodes were expected to wait to become cluster members.

There still exist a number of questions regarding the performance of the HCT MAC protocol regarding the chosen metrics. It must be further clarified the the dependence of its performance on spatial distribution of nodes and mobility pattern. Therefore, a desired result is to predict its performance according to such characteristics of the network.

7. ACKNOWLEDGMENTS

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