Performance Evaluation of a Real-Time MAC Protocol for MANETS

Marcelo M. Sobral[1], **Leandro B. Becker** [1]

[1] Departamento de Automação e Sistemas
Universidade Federal de Santa Catarina (UFSC) – Florianopolis, SC – Brazil

{sobral,lbecker}@das.ufsc.br

Abstract. *A wireless ad-hoc network for mobile nodes is characterized by a highly-dynamic topology that cannot predict the duration of the links among the nodes and neither the density of nodes within the network. Our previously proposed HCT (Hybrid Contention/TDMA) Real-Time MAC protocol provides a kind of short-range resource reservation policy for groups of nodes, which lasts while the participant links are available. Moreover, it adapts to continuous topology modifications. This paper analyses the performance of the HCT MAC protocol in special networks scenarios that deal with nodes mobility. Obtained results show that exists a direct relation between mobility degree and expected clustering performance of the protocol, which influences its real-time performance.*

1. Introduction

A new generation of applications will require communication capacity in environments without any infrastructure. To make the problem more complex, such applications might be composed by mobile nodes, which rely on wireless links to achieve communicability. The literature recently proposed the term MANET (*Mobile Ad-Hoc Networks*) to represent such application domain. Some MANET applications present an additional complexity because they require real-time guarantees with respect to the communication medium. An example of such applications is vehicle-to-vehicle (V2V) systems [Voelcker 2007], like platooning, which helps to reduce traffic congestions and provide safe driving. New areas of research in the space community have similar communication requirements, as for example in distributed satellite systems (DSS) [Bridges and Vladimirova 2009] where multiple spacecraft in varying configurations are used to achieve a mission's goals collaboratively.

In this context, we recently proposed a hybrid medium access control mechanism named HCT (Hybrid Contention/TDMA-based) MAC [Sobral and Becker 2008], which aims to provide a deterministic medium access by means of resource reservation. It also supports reconfiguration and mobility by using a contention-based approach. Therefore, it assumes that the mobile nodes are self-organized in clusters, used exclusively to support the allocation of time-slots within the corresponding member nodes. Ideally, clusters should be defined in a way that it allows as many nodes as possible to operate in resource-reservation mode. In [Sobral and Becker 2009] we addressed the problems related to the dynamic self-organization of clusters. More specifically, we presented an approach to establish the clusters in a distributed and autonomous way, taking into account the *neighborhood quality*, which stands for the communication quality among neighbour nodes.

An excellent neighborhood quality would imply a high number of nodes communicating to the cluster-head with suitable link quality, thus improving the amount of clusterized nodes and cluster *longevity*. By definition, more clusterized nodes and more lasting clusters increase the operation in resource-reservation mode of the involved nodes.

In this paper we present a performance evaluation of the HCT-MAC to assess the resulting cluster formation in specific scenarios dealing with nodes mobility. Our previous performance evaluation used only static scenarios. We focused this new evaluation in quantifying (i) cluster longevities and (ii) rate of clusterized nodes. Rate of clusterized nodes gives the average number of nodes that are cluster members. We also investigate the relation between both results and the neighborhood size, which gives the number of neighbors that receive frames sent by a node.

The remainder of the paper is structured as follows: section 2 gives a brief overview of the HCT, including its clustering strategy and how it computes the neighborhood quality. Section 3 presents preliminary results that show the resulting clustering rates and longevities for small networks which nodes move according to some mobility scenarios, and the consequent neighborhood sizes. Finally, section 4 concludes the paper and points out some future directions of our work.

2. Overview of HCT MAC Protocol

In [Sobral and Becker 2008] we presented the Hybrid Contention/TDMA-based (HCT) MAC, which aims to provide a time bounded medium access control to mobile nodes that communicate through an ad-hoc wireless network. A key issue in this protocol is to self-organize nodes in clusters (i.e: set of neighbor nodes), as a mean to solve the problem of timely transmission of messages. Our protocol assumes as basic requirements a periodic message model, where the assignment of time-slots must be done within clusters. A competition strategy is adopted, without the need of a global coordinator nor scheduler, in such a way that time-slots are iteratively allocated by the nodes.

The HCT-MAC is a hybrid protocol because it has both contention-based and resource-reservation characteristics. A TDMA-based MAC protocol divides time in so-called time-slots, being responsible to assign one or more time-slots to each node. To solve this problem, the HCT-MAC uses a contention-based approach to allocate slots: if a node knows which slots are idle, it can try to use some of them, chosen randomly, and then verifies if any collision has occurred. For each chosen slot, if there was no collision, the node may assume that the slot is allocated. For the remaining slots, it can repeat the procedure until all the needed slots are allocated or, in the worst-case, no slots are available anymore. This protocol assigns the time-slots iteratively, until the allocation stabilizes, i.e. the nodes allocate all needed slots. The already allocated time-slots can be used just like in a TDMA protocol, revealing the resource-reservation aspect of the HCT-MAC.

The timing in the HCT has a periodic and hierarchical structure, as ilustrated 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, and is divided in *superframes*, which are assigned to the clusters. Superframes are all equal in size, which means that they contain the same number of *time-slots*, plus two control frames called *beacons*. Therefore, clusters need to allocate superframes, and cluster members allocate

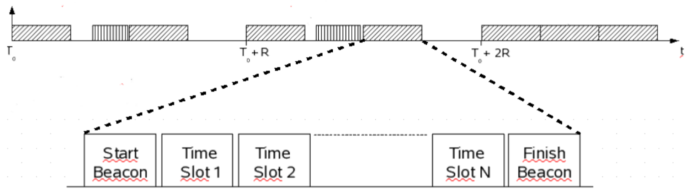


Figure 1. Timing in the HCT: cycles of length R divided in superframes

time-slots within those superframes.

The TDMA component of the HCT, described in [Sobral and Becker 2009], depends on the clustering of the nodes, which must be obtained in a self-organized manner. This is due to the fact that the HCT protocol is designed to be used in mobile ad-hoc networks, where the nodes are not previously aware of the topology, neither of their neighborhoods. The chosen approach relies on initial contention-based access, that shifts gradually to time-based as clusters are formed and become stable. That means, as nodes self-organize in clusters, they can reserve bandwidth and transmit messages in a timely manner. This implies procedures for the neighborhood discovery, the collection of information to support the independent choice of the best candidate nodes to start clusters, and the announcement of new clusters and ingress of interested nodes.

2.1. The Clustering Approach

As described in [Sobral and Becker 2009], clusters are simply sets of nodes that agree to share a superframe, which represents a portion of the network bandwidth. A key element in the cluster topology is the cluster-head, a special node responsible to start cluster transmissions, to account for idle and used time-slots, and to report successful transmissions. Ideally, the cluster-head should be the node with the best neighborhood quality within the region to be covered by the cluster, in order to minimize the probability of errors in transmissions inside the cluster. In our proposed HCT it is not possible to determine exactly the nodes with best neighborhood quality, since no node has a global view of the network, and no global information is maintained by the protocol. But the information about the neighborhoods, estimated based on the received frames, can be collected and shared locally among the nodes to help them to decide to become or not cluster-heads. Thereby, the cluster-heads can be self-elected according to the information they are able to obtain about the nodes around them.

The rule for establishing clusters is guided by the fact that the cluster-head should be the node with the best neighborhood quality (NQ). The quality of a neighborhood of a node is defined in this work as a function of the qualities of links between this node and each of its neighbours. It expresses both the quantity of neighbours and their link qualities. A high NQ means few or no transmission errors (missed or corrupted frames) or, in other words, a high frame reception rate. Therefore clusters have higher probability to be stable, because more frame losses would force member nodes to try to bind to other clusters.

2.2. Neighborhood Quality Computation

HCT needs to compute continuously the Neighborhood Quality (NQ). The NQ of a node depends on the quality estimation of individual links to its neighbours.

In [Sobral and Becker 2009], NQ was defined as a moving average of the sum of RSSI-based measures of received frames. The chosen link quality estimator (LQE) derived from the RSSI of the received frames because, as demonstrated in [Zuniga and Krishnamachari 2004], there is a relation between the expected PRR (Packet Reception Rate) and the RSSI. However, as discussed in [Baccour et al. 2010], this kind of LQE does not fully capture the properties of a link. To overcome this problem we are moving towards the adoption of F-LQE [Baccour et al. 2010], a new link quality estimator that combines several link properties to better characterize its quality.

The HCT protocol uses LQE also to increase the probability of nodes with better link qualities (relative to the cluster-head) to become members of a cluster. When a node tries to ingress a cluster, it waits for the Start Beacon control frame, chooses randomly an idle time-slot and then transmits in the selected time-slot. If the cluster-head receives such transmission, it acknowledges it in the Finish Beacon control frame but with probability p_q; it means that the cluster-head ignores with probability $1-p_q$ the received transmission. This probability p_q is higher for transmissions received with high link quality. Thus, HCT tries to establish clusters with higher neighborhood quality, increasing the probability that their member nodes are those with better link quality.

2.2.1. F-LQE

[Baccour et al. 2010] defines F-LQE as a link quality estimator based on four measured properties: packet delivery (SPRR), asymmetry (ASL), stability (SF) and channel quality (ASNR). By combining these properties, it aims to provide a more accurate link quality estimation. The instantaneous quality $LQ(i)$ of the link of node i is expressed as a membership in the set of good links, according to a fuzzy rule shown in equation 1. The overall quality $FLQE_i(\alpha, w)$ of node i is averaged over a window of w received frames (suggested to be 30), and smoothed according to a parameter α (suggested to 0.6), as can be seen in equation 2. Its attractiveness to the HCT resides both in the ability to capture important aspects of link quality and the smoothness and stability of generated values.

$$\begin{aligned} LQ(i) \;=\; & \beta \cdot min(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) + \\ & (1-\beta) \cdot mean(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) \end{aligned} \quad (1)$$

$$FLQE_i(\alpha, w) = \alpha \cdot FLQE + (1-\alpha) \cdot LQ(i) \quad (2)$$

2.2.2. F-LQE metrics within HCT

To compute its four link properties (packet delivery, asymmetry, stability and channel quality), F-LQE needs to keep a history of measured values. They must be calculated for each individual link, i.e., a node computes their values individually for each one of its neighbours. But since HCT transmits always in broadcast, some adjustments are needed to compute these measures:

- **Packet delivery:** it depends on SPRR (Smoothed PRR), that accounts for the actually received frames compared with the transmitted ones. HCT can obtain this estimator by the inclusion of a sequence number within each frame. Therefore, receiver nodes can compare the number of actually received frames and the interval of sequence numbers to compute the PRR.
- **Channel quality:** easily obtained from the RSSI of received frames subtracted by the noise floor.
- **Stability:** it corresponds to the variability of the PRR, as obtained in *Packet delivery*. The F-LQE defines the stability as the coefficient of variation, i.e. the reason between standard deviation and mean.
- **Asymmetry:** the hardest to obtain, because it depends both on *PRRup* and *PRRdown*. *PRRdown* is straightforward, since it is the same as the *Packet delivery*, but *PRRup* is the *Packet delivery* as seen by the neighbour. It is not feasible to make the neighbour to transmit its *Packet delivery*, but *PRRup* could be derived if the neighbour would acknowledge each received frame. Unfortunately, since HCT uses only broadcasts, this is also not feasible. Therefore, it was decided to exclude this metric from F-LQE within HCT

2.2.3. Using F-LQE to Compute the Neighborhood Quality

The Neighborhood Quality (NQ) was modified to better explore the F-LQE. Obviously, a good neighborhood should be composed by neighbours with good link quality estimations. It means it depends both on the quantity of neighbours and their corresponding LQE values. As defined in [Sobral and Becker 2009], NQ was computed as the sum of the LQE values, but with the adoption of F-LQE it would be better to calculate the product of the F-LQE values (L_{ij}), as shown in equation 3. The parameter L_{REF} (*Link Quality Reference*) was chosen to emphasize good links. Thus, NQ_{ij} value increases if $L_{ij} > L_{REF}$, otherwise it decreases.

$$NQ_j = \|N_j\| \prod_{i \in N_j} (1 + L_{ij} - L_{REF}) \tag{3}$$

Finally, to avoid sudden changes in NQ_j, which can appear when frames from neighbours are missed for just few cycles (for instance due to external interferences), a smoothing of NQ_j is applied as seen in equation 4 (parameter $\beta \in (0, 1]$). The resulting metric is called SQ_j (Smoothed Neighborhood Quality).

$$SQ_j = \beta \cdot NQ_j + (1 - \beta) \cdot SQ_j \tag{4}$$

3. HCT Evaluation

HCT was designed to be used in networks containing mobile nodes. In such scenarios, it is expected that clusters arise and disappear dynamically, as the network changes its topology. Depending on the mobility degree of the network, reorganization of clusters are expected to occur more or less frequently. Since nodes transmit in resource-reservation mode only when they are members of clusters, the clustering performance has great importance to the HCT. The clustering performance can be expressed as:

- **Clustering rate:** rate of nodes that are members of cluster.
- **Cluster longevity:** expected longevity of clusters, represented by the interval between the moment a node becomes a cluster-head and the moment it reverts to single node (this occurs when its cluster becomes empty).

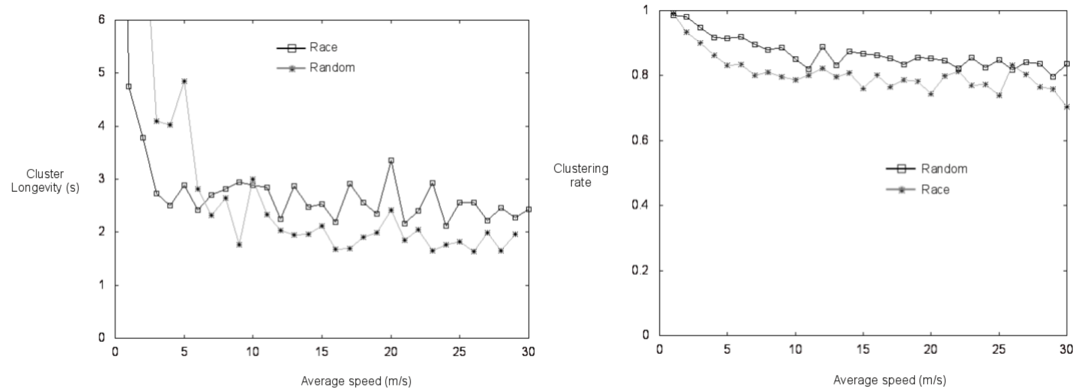
An important aspect of HCT performance is the neighborhood size, which gives the number of neighbours that receive frames sent by a node. This metric can be investigated both through its average over all transmission cycles, and by a ratio to the potential neighborhood (i.e. the nodes that can receive the frame). We investigate here a possible relation between clustering rate, longevity, and neighborhood size. This might hold because as more nodes are members of clusters, and consequently operate in resource-reservation mode, less collision is expected and more nodes receive each frame.

The HCT performance in networks with mobile nodes was investigated by means of simulations. They were executed using a simulation model of HCT developed using the Omnet++ simulation framework [Varga 2001], assuming a IEEE 802.15.4 physical layer. The HCT models uses as physical layer the project Castalia, maintained by the National ICT at the University of Australia [Pham et al. 2007], which implements the signal model proposed in [Zuniga and Krishnamachari 2004] and simulates a IEEE 802.15.4 compatible radio. This model derives the PRR (Packet Reception Rate) of each link according to a path loss model as function of the corresponding SNR (Sound to Noise Ratio). The Castalia model needed to be modified to support mobility, in such way it recomputes its internal PRR matrix each time a node moves.

Two special simulation scenarios were created:

1. **Random:** the simulations are composed by networks with changing topologies according to random node speeds and increasing speed averages. Nodes were scattered and enclosed within a square region, moving in constant directions and reflecting on the walls. These scenarios should demonstrate a pessimist situation for the HCT, since few patterns can exist in such networks. Indeed, only the average speed of the nodes dictates the duration of their links. This mobility model can be related to movements in the urban space, like people moving in squares or malls.
2. **Race:** the networks were composed by nodes that move all in the same direction, but with slight different speeds. In these scenarios, the relative speeds between nodes are small and thus it is expected a less frequent cluster reorganization. This mobility model can be related to cars moving along a street or highway, people runnning in a competition, and other cases where comunnicating devices move in the same direction.

In both cases the networks were composed by 20 nodes. For each of these scenarios, the maximum speeds varied between 1 and 40 m/s. For the random mobility model, the speed of each node was chosen from an uniform distribution between 0 and the maximum speed, and the direction was chosen randomly and only changed when the node reached the boundaries of the square area. For the race model, the speeds were chosen from a normal distribution, using as mean half of the maximum speed and a standard deviation such that the speeds stay below the maximum speed with probability 0.99. In both models the speeds do not change along the simulations. Each simulation generated statistics for the clustering rate and cluster longevity. The cluster longevity was expressed as



(a) Cluster longevity as function of speed (b) Clustering rate as function of speed

Figure 2. Clustering performance

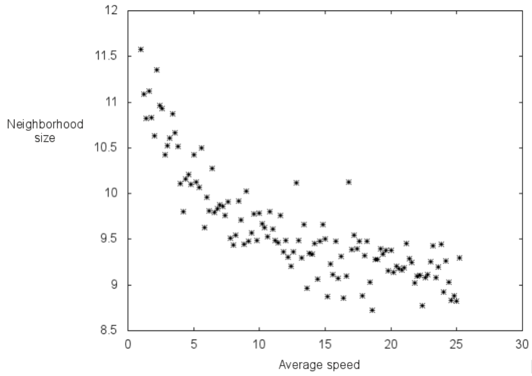
a histogram and also as an expected value, calculated from the histogram. The clustering rate was shown as the number of clusterized nodes as function of the average speed.

3.1. Obtained results

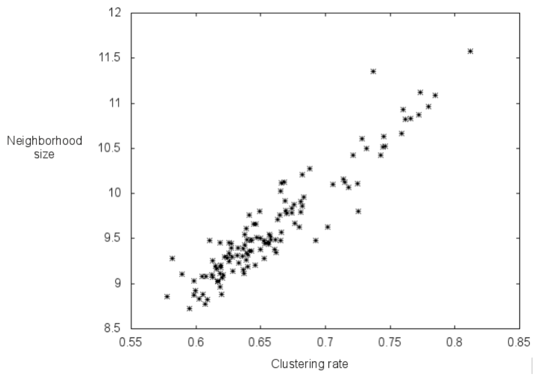
The results for the cluster longevities are shown in figure 2(a). The plots show that cluster lifetimes drop faster from 0 to 5 m/s, and for greater average speeds it stays around 1.5 s. The race scenario gives a slight better cluster longevity for higher speeds. Since in this kind of simulation the nodes move all in the same direction, but with slight different speeds, their smaller relative speeds allow more durable links. In the case of the random scenario, although the relative speeds are potentially higher because nodes can move in any direction, the more dense resulting network favors the cluster longevities. In the simulation, the network density effect prevails for smaller average speeds.

Clustering rate, another relevant metric of performance of HCT, is shown in figure 2(b). There is a slight difference between random and race scenarios, with the random one giving higher clustering rates. It must be noted that in the race scenario the relative speeds between nodes are lower than in the random scenario. This leads to more durable memberships, since it takes longer to a node to get out of sight of its cluster-head. But since the nodes are continuously scattering along the race line, it is more probable that once a node gets single, it will remain longer in this state due to the lower network density.

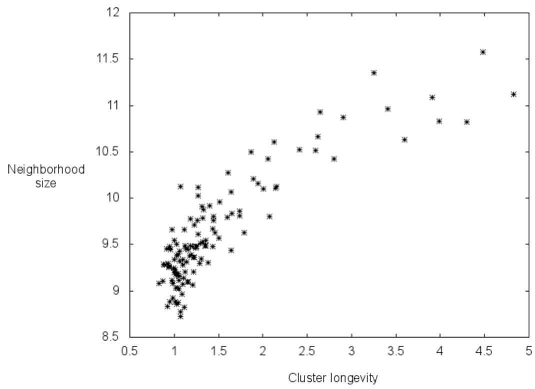
Both clustering rate and longevity expresses the behaviour of clustering within the HCT protocol in the simulated scenarios. The resulting performance, in the point of view of an application, can be seen in the rate of messages each node can transmit in resource-reservation mode, and the number of neighbours that receive those messages, known as neighborhood size. Therefore, the neighborhood size becomes an important way to investigate the success of HCT in delivering frames. In the simulations of the random scenario, the neighborhood sizes were averaged for each simulated speed and the results are shown in figure 3(a). It decreases as the speeds get higher, that can be related to the clustering performance. In figure 3(b) the neighborhood size is related to the clustering rate, revealing a linear relation. As shown in figure 3(c), a similar relation to the cluster longevity was not found.



(a) As function of average speed (m/s)



(b) Relation to clustering rate



(c) Relation to cluster longevity

Figure 3. Average neighborhood size

4. Conclusions and Future Work

This paper extended previous performance evaluation already conducted for the HCT MAC by adopting scenarios that deal with the mobility of nodes. Previous evaluation only considered static nodes.

The evaluation presented in this paper was performed by means of simulations using two different mobility scenarios: (i) random movements and (ii) race emulation. The measured clustering performance was expressed as clustering longevity, clustering rate, and neighborhood size. As expected, the clustering performance decreases as nodes move at higher speeds, as this creates more dynamic topologies, demanding more cluster reconfigurations. It is also observed that both clustering rate and cluster longevity decreases with an exponential-like curve as function of the speed of nodes.

Curiously, the race-emulation scenario presented worse results in these respect, although the smaller relative speeds between nodes can favor longer cluster lifetimes. This is due to the fact that the race-emulation generates a more sparse network, so it is less probable that a single node has a satisfactory neighborhood to clusterize.

Another observation is that, as expected, the neighborhood size also decreases as node speed gets higher. However, it shows a linear relation of the neighborhood size to the clustering rate, that gives the rate of nodes that are operating in resource-reservation mode. This relation was not found when compared to the cluster longevity. The neighborhood size corresponds to the quantity of nodes that successfuly receive frames from their neighbours, and is a measure of performance of the data delivery in the protocol. Therefore, a higher clustering rate improve the data delivery, but the same cannot be said about the cluster longevity.

Despite this evaluation, there exists a number of open questions regarding the efficiency of the HCT protocol in mobile networks. Firstly, it must be further investigated the scalability of the protocol compared to the network size and mobility degree. There must exist a maximum node speed below which the protocol has a satisfactory performance. The overall performance of the protocol depends on the clustering performance, which is influenced by the neighborhood quality. Currently, the neighborhood quality is calculated as a function of the quantity of neighbours and their link qualities, and its instantaneous values are used to support clustering decisions. The neighborhood quality could be changed to try to anticipate the neighborhood behaviour, increasing if the neighborhood is becoming better or decreasing otherwise. Finally, clusters could change their cluster-heads to adapt to changes in the neighborhood qualities of the cluster members. A cluster-head which detects that its neighborhood quality is significantly lower than one of its cluster members could delegate the cluster-head role to that node and revert to single node.

5. ACKNOWLEDGMENTS

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