Distributed Multi-Level Cooperative scheme for QoS Support in Public Safety Networks

Fabien Esmiol*†, Stéphane Rousseau*, Vania Conan*, Christian Bonnet†

*Thales Communications
Colombes, France
Email: surname.name@fr.thalesgroup.com

†Institut Eurecom
Sophia antipolis, France
Email: surname.name@eurecom.fr

***Abstract*—A Public Safety Network (PSN) is a particular kind of wireless ad hoc network which provides a communication support for Public Safety Users. Use-cases are numerous in terms of both deployment scenarios (e.g. mobile or fixed, small or large scale) and services (Push To Talk, Mail reporting, video streaming). Extreme conditions encountered after an earthquake or floodings may impede the use of any communication infrastructure. Maintaining robust and efficient communictions is such harsh conditions is a major challenge. QoS requirements lead previous studies towards TDMA based radio resource management combined with clustering techniques for scalability purposes. In this paper we investigate how both Push-To-Talk and Mail Reporting services can be supported in such networks. The key contributions are threefold: i) identification of remaining issues within TDMA/Clustered networks ; ii) proposition of a novel radio resource management protocol ; iii) evaluation of performance gains of the novel solution. We show that both services (Push-To-Talk and Mail reporting) can be supported in a Public Safety Network and that our solution outperforms the previous ones. Finally, we present further identified targeted works to improve our solutions.**

***Keywords*-Resource reservation, MAC clustering, hierarchical network, cooperative scheduling, QoS, public safety**

I. INTRODUCTION

A Public Safety Network (PSN) is a wireless Ad Hoc Network that aims at facilitating communications between Public Safety Users during a critical intervention. It is often the only alternative to infrastructure networks (Wireless Mesh Network, Cellular Network) that become inoperative after a flood or other natural disaster [1], [2]. In PSNs, unlike Wireless Mesh Networks, it is not possible to benefit from special features such as directional antennas. A PSN can be seen as an Ad-Hoc Network in charge of providing Wireless Mesh Network performances. This introduces novel self configuration, management and QoS support challenges. Moreover, the required services are numerous and varied: Push-To-Talk communications, access to video surveillance, or other elastic traffic such as Mail reporting. Each of them has particular QoS requirements and each must be dealt with in a specific way from a network management point of view.

To ensure guaranteed services in such a network, different approaches have been proposed. One should be able to reserve resources on the wireless medium to avoid interferences from other transmissions on that resource. Such resources may be TDMA (Time Division Multiple Access) slots (time resources), or FDMA (Frequency Division Multiple Access) frequency carriers, or codes in CDMA (Code Division Multiple Access), or a combination of the above. The major challenge is to schedule the transmissions along the paths from sources to destinations, in such a way as to avoid interferences. Theoretical centralized cross-layer resource allocation schemes have been proposed [3]. For a time varying Ad-Hoc Network with interferences, there are randomized approximations for throughput optimal scheduling.

Moreover a practical scheduling algorithm should be distributed and its implementation in real equipment feasible. Clustering nodes that are in visibility of one another greatly facilitates scheduling implementation [4]. Such neighboring nodes are grouped together into subsets called clusters. Each cluster possesses a special node, the cluster-head, which is in charge of making all resource reservations for all the transmissions involving the nodes within its cluster. However, this approach does not prevent interferences between adjacent clusters and coordination between cluster-heads is required in order to provide QoS guarantees.

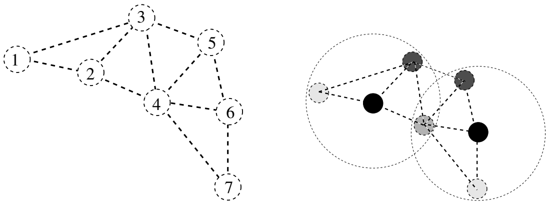
The question that we address in this paper is the following: *to which level should the cluster-heads coordinate their individual schedules ?* We propose a new fully distributed multi-level cooperation algorithm which reduces cross-interferences on reserved resources in a clustered wireless network. Two variants are described and evaluated, one for the Push-To-Talk service and one for Mail Reporting service. We assess the performance of the algorithm against various topologies and traffic conditions and compare it to a random slot assignment method. We show that introducing cooperation between clusters improves overall performances of the network.

The remainder of the paper is organized as follows. In Section II, we make a complete description of the wireless network model and present in detail how radio resources are managed in a clustered network. In Section III, we present our contribution that consists in defining different cooperation level between clusters and one reservation protocol for both Push-To-Talk and Mail Reporting. In Section IV, we explain the simulation environment we used and the results we obtained for the two considered services. Finally, in Section V, we expose the related work and we conclude in section VI.

II. WIRELESS NETWORK MODEL DESCRIPTION

A. Cluster: network node organization

We consider a PSN whose Medium Access Control layer (MAC) is organised in clusters [4], [5]. More precisely, a cluster consists of one central node, called the cluster-head (CH), which is in direct visibility of all the other nodes in the cluster: all nodes in the cluster are one-hop neighbors of the CH.



(a) (b)

Figure 1. On the left, a Public Safety Network composed of 7 nodes is represented. On the right, the same network is organized in two clusters. Nodes 2 and 6 in black become Cluster-Heads. All other nodes are Cluster-Members. Communications between clusters are ensured by special Cluster-Members, called Cluster-Relays. Both node 4 and the pair of nodes $(3, 5)$ are Cluster-Relays.

Figure 1 depicts an example of a PSN layout. Routers are represented by nodes and wireless links by dotted lines. The network is composed of 7 nodes but their number can be up to 100 in reality. To address scalability nodes are grouped into subsets called clusters. In the example nodes 2 and 6 in black become Cluster-Heads. All other nodes are Cluster-Members. Communications between clusters are ensured by special Cluster-Members, called Cluster-Relays. Depending on the used MAC layer, two kinds of Cluster-Relays may appear. In this example Both node 4 and the pair of nodes $(3, 5)$ are Cluster-Relays.

B. TDMA-Frame: radio resource organization

Within each cluster, radio resources are organized into slots that form a frame. The TDMA-Frame is composed of four parts as shown in Figure 2. The first part is the beacon sent by the cluster-head to its members to synchronize with them. In the second part, the CH informs its members of the schedule decisions correspoding to the previous requests. The third part is used by the members to send their requests for the next TDMA-Frame to their CH. Finally, the fourth part is the slots used to transmit data.

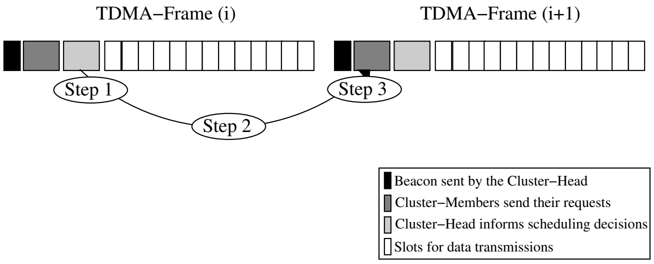


Figure 2. The first part is the beacon sent by the cluster-head to its members to synchronize with them. In The second part, the cluster-head informs of the schedule decisions of the previous requests to its member. The third part is used by the members to send their requests for the next TDMA-Frame to their cluster-head. Finally, the fourth part is the slots used to transmit data.

After having received requests (step 1 in Figure 2) from its cluster members, the CH decides how to schedule them in the upcoming TDMA-Frame (step 2 in Figure 2). It uses the second part of the next TDMA-Frame to inform its cluster members of its decisions (step 3 in Figure 2).

C. Illustrative example and motivation

In this section we describe an example of the entire reservation process from the service establishment request of an end-user up to the shutdown of the communication. This will serve to motivate clearly our study and highlight the targeted challenges.

1) Example: For every communication request entering the network the following four steps are followed: i) the source node sends a radio resource request all along the multi-hop path towards the destination, ii) if possible, the resource is reserved within each cluster, iii) the communication is established providing the end-user service, iv) upon termination of the communication the radio resources are freed along the path. This study focuses on step ii). Establishing the communication is considered to be possible if the needed radio resources are available within each cluster all along the path. To that end each cluster tries to schedule the new flow into the TDMA-Frame.

2) Motivation: Clutering aims at reducing the complexity of scheduling at MAC layer level. It ensures that within a cluster, all transmissions will be sent successfully, i.e. without any collision, and this solution tackles the scalability issues. However, when clusters schedule their communications independently of one another, collisions may still arise from communications scheduled in neighboring clusters. This point is crucial when one tries to ensure End-to-End QoS for multi-hop (and multi-cluster-hop) communications.

Clusters have to be coordinated in order to avoid such inter-cluster interferences. However several degrees of coordination are possible between clusters. The main question we address is : *Which degree of cooperation is the best suited depending on the network requirements in terms of QoS or delay*. Section III describes a solution that consists in grouping several clusters in one super-cluster and selecting a cluster-head leader to manage radio resources at an upper level.

III. SOLUTION : MULTI-LEVEL COOPERATIVE CLUSTERING

The cooperation scheme consists in grouping the clusters into subsets of adjacent clusters to form a cooperation group (CG). A CG is composed of a cooperation leader (CL) and cooperation members (CMs). As we shall see clusters in the CG exchange simple control information in order to avoid the assignment of the same time slots twice.

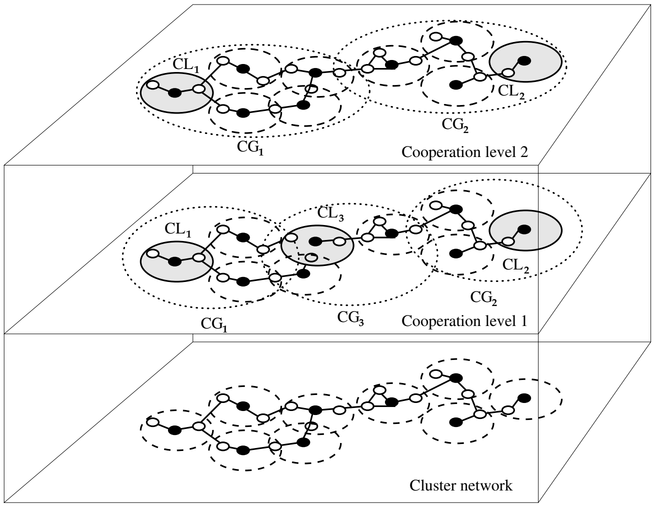


Figure 3. The bottom part represents a network organized into clusters. The middle part shows level 1 cooperation group formation. Note that each cluster only belongs to one cooperation group. The top part shows level 2 cooperation group formation. The cooperation groups are bigger and gather more clusters, and consequently there are less cooperation groups.

To form the cooperation groups the same clustering algorithm is run as to form clusters, but instead of grouping nodes (to form clusters), one groups clusters (to form what we called cooperation groups). In this way one of the clusters in the group is elected cooperation leader and its neighboring clusters become cooperation members. A CM belongs to a single cooperation group. The evaluation of the performance shown in section IV is performed with the Linked Cluster Architecture (LCA) clustering algorithm [5] for both clustering and cooperation group formation.

One would wish to avoid interferences in the cooperation groups in the same way as one avoids interferences in the clusters. One option would be to schedule the entire cooperation group. This would require that all clusters send their demands, a measurement of each link quality, and estimates of the position of the nodes (since we use a SINR based model). This is not however a practical option. Carrying this volume of information at the required scheduling rate possibly over multi-hop paths (between a CM and the CL) is the first issue. And scalability of scheduling techniques is too limited, especially for dense networks with crowded cooperation groups.

Instead we propose a more efficient alternative that retains the above principle, but remains scalable and efficient. Exactly as when no cooperation occurs, each cluster inside the cooperation groups separatly calculates the number of time slots they require to schedule their demands. Each cluster sends its needs (total number of slots) to the cooperation leader (CL) in its cooperation group. The CL assigns a distinct slot range to each cluster. Finally, the CL sends back to the cooperation members the id of the first slot and the number of slots assigned to each cooperation member. This mechanism prevents collisions between the communications of members of a CG while limiting the amount of exchanged overhead control information.

In the study we consider up to three levels of cooperation, although one could theoretically use more. Level 0 corresponds to no cooperation. In level 1 cooperation every adjacent cluster from the cooperation leader joins the cooperation group. Level 2 adds the second rank of adjacent clusters. In another words, the level represents the radius counted in number of traversed clusters to go from the cooperation leader to its farthest cooperation members. Figure 3 shows an example with two levels of cooperation.

The formation of cooperation groups implies an additional scheduling step between intra-cluster scheduling and node transmissions. An example of all the steps from node request to node transmission is depicted in Figure 4. The 2 first steps are the same as with no cooperation. Each node sends its requests to its CH. Let's then consider the messages going from the cooperation members to the cooperation leader. Each CH (as group member) sends one piece of information (the number of slots it requires) to the group leader. This message traverses the group in a hop by hop fashion to reach the group leader. On average the overhead this incurs is proportionnal to the average number of 1-hop clusters in the cooperation group for any level of cooperation.

The cooperation leader then returns two pieces of information to each cooperation member identifying the slot range it is allowed to use. The cooperation leader may broadcast a control packet to communicate all the slot ranges to all the group members. There are either 2 or 3 hops between CHs from adjacent clusters (depending on the kind of relay nodes between them). Each member forwards the packets to its neighbors. The CH of each cluster broadcasts the packet to their relay nodes, who then send the packet to the adjacent CHs. Thus, the cooperation leader has to broadcast the slot ranges only once with an average path length of 2.5.

In levels 2 and 3 of cooperation the one-hop cluster must relay this message to clusters farther away. The latency to etablish a communication corresponds to the longest path length (bounded by [2;3] for level 1 and [6;9] for level 3).

This analysis confirms that signalling overhead is stable while latency for communication etablishment increases continuously for increasing levels of cooperation.

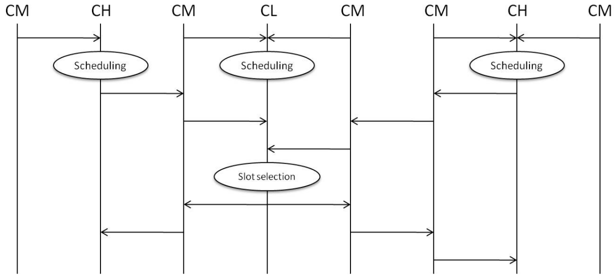


Figure 4. This figure describes the delay of communication etablishment in a cooperation group. The CHs estimate the number of resources needed for the communications within their cluster and send this number to the cooperation leader. The cooperation leader performs a slot selection once it received all the requests from the CHs in the cooperation group. The cooperation leader finally sends the result of the slot selection to the CHs.

A. Selecting the slot ranges

The purpose of the cooperation algorithm is to select the range of slots to be assigned to each cluster (see Algorithm 1. Its only input is the number of resources (i.e.; time slots) that each cluster in the cooperation group requires to schedule its transmissions. The algorithm assigns consecutive slots to each cluster. A slot by slot assignment would require to inform each cluster of the slot IDs of each slot assigned to it. The amount of control data to be sent would be then bounded by the total number of slots of the TDMA-Frame. By assigning consecutive slots, only two items, the IDs of the first and last slots of the assigned range, need to be sent. The major pitfall the algorithm must avoid is to always assign the first slots of the TDMA-Frame to the different clusters. This would increase the probability of inter-cooperation group collisions. The algorithm avoids it by considering the number of slots that are not used in the TDMA-Frame (called free slots) and by randomly adding them to the different clusters.

Algorithm 1 This code describes our algorithm to assign portion of the TDMA-Frame to each cluster of a cooperation group.

```
cluster.$Ns$        ▷ Entry parameter : Number of slots required
cluster.$fs$ = 0        ▷ first slot index
cluster.$ls$ = 0        ▷ last slot index
$currentSlotIndex$ = 0   ▷ index of the next available slot id
$freeSlot_{ns}$ = 0        ▷ number of free slots
$freeSlotArray_i$ = 0        ▷ array of the free slots id
$freeSlotIndex$ = 0 ▷ current index in the array of free slots
$freeSlot_{ns} \leftarrow Frame_{capacity} -$ cluster.$Ns$
for $i = 0$ to $freeSlot_{ns}$ do
    assignRandomSlot($freeSlotArray_i$)
end for
sort($freeSlotArray$)
for All cluster do
    cluster.$fs$ = $currentIndex$
    cluster.$ls$ = $currentIndex$ + cluster.$Ns$
    while ($freeSlotArray_{freeSlotIndex} \leq currentIndex$ + cluster.$Ns$) do
        cluster.$ls \leftarrow$ cluster.$ls + 1$
        $freeSlotIndex \leftarrow freeSlotIndex + 1$
    end while
    $currentSlotIndex \leftarrow$ cluster.$ls + 1$
end for
```

B. End-to-End communication establishment protocols for PTT and Mail reporting services

The two services are different in terms of QoS requirements. For Push-To-Talk, a real-time QoS with low packet loss ratio is required. To achieve such a QoS ensurance, we propose that the Cooperation Leader makes the reservation decision as it is has a broader view on slot occupancy. Mail reporting does not require such a stringent QoS guaranty. In order to reduce latency for communication establishment, we propose that the CH be in in charge of reservations. This refers to the example given in Section II-C and more precisely to the second step of communication establishment.

IV. PERFORMANCE EVALUATION

In our simulations we consider a network of 100 nodes. The nodes are randomly placed in a 1000m x 1000m area with a constraint of maximal and minimal distances between nodes to ensure full connectivity of the generated topologies, and to monitor average node degree.

We assume synchronization of all the nodes in the network. The TDMA frame is composed of 40 slots. The maximum accepted transmission rate for each slot is a function of the SINR value [6]. For example, a communication between two nodes would use a single slot at the best rate (SINR = 21dB), 2 slots at the middle rate (SINR = 12dB) and 4 slots with the worst rate (SINR = 8dB).

We generate random source-destination pairs as traffic demands. Each traffic demand has a need corresponding to one slot at the highest rate. Flows are real-time constant bit rate. For each routed demand, we assess the performance of the cooperation over different network densities. We compute the throughput as the total number of scheduled packets on the network. Collisions between packets is counted as packet loss. We increase the number of accepted demands until the network is saturated, that is when one of the clusters has used all its resources and cannot accept a new flow.

We consider the physical interference model(SINR). In this model, the power received is the emission power multiplied by the channel gain given by the following equation: $PR_{uv} = P \times G_{uv}$
The channel gain represents the signal attenuation over the

distance and is given by the equation: $G_{uv} = \frac{1}{(d_{uv})^{\alpha}}$ where $(d_{uv})^{\alpha}$ is the distance between u and v and α is the path loss exponent. A link between two nodes exists if the SINR ratio the following equation is above a given threshold: $SINR_{uv} \geq \frac{P\times G_{uv}}{\sum_{w\in V, w\neq u} P\times G_{wv}+\eta}$
This equation gives the power received by the node v coming from u on the sum of the interferences on the network which is the power received by the node v from all the nodes on the network but u. If the SINR ratio at the destination node v is above a given threshold, the packet is succefully received by v. Else, the packet is considered lost.

A. Level of cooperation performance analysis for Push-To-Talk service support

First we look at push-to-talk applications. PTT do not support delay and a very low packet loss rate (under 1%). As mentioned in Section III-B, to satisfy the requirements, the cooperation leader performs admission control of the flows. Following a new flow request all CHs on the path ask for new resources to the cooperation leader. If there are enough resources available for the whole flow, the flow is accepted. Else, the flow is refused and must wait for one of the current flows to finish.

For performance analysis purposes, we compare the number of accepted flows for each level of cooperation, and we also compare the packet loss ratios observed for each new accepted flow. Indeed, a cooperation leader does not have a perfect knowledge of all used resources and cannot anticipate all interferences. Increasing the cooperation level tends to minimize collisions due to bad scheduling. On the other hand, the admission control will be clearly more restrictive.

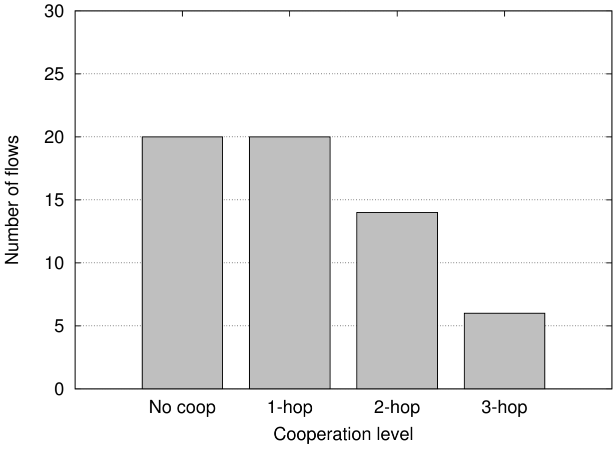


Figure 5. Number of accepted flows for each level of cooperation.

In Figure 5 we compare the different cooperation level solutions in terms of number of accepted communications. We consider that the network is not able to support the Push-To-Talk service in two cases: if the cooperation leader does not find enough resources to schedule the new flow or if the packet loss ratio becomes too high for all Push-To-Talk accepted communications. Under those assumption, without cooperation between clusters and for a level 1 cooperation scheme, the number of PTT communications reaches 20. For both, the simulation has stopped because the packet loss ratio becomes too high for all of the 20 PTT communications. As a main consequence, none of them were supported even if the resource reservation process validated their schedule. Regarding the other level of cooperation, the second level cooperation scheme accepts 14 flows and the 3 level one only 6 flows. The level of cooperation impacts considerabily on admission control. In this case the number of accepted communications is reduced by half, clearly not a negligeable drop. Once accepted, communications can be the subject of unforseen collisions that can degrade notably the QoS guaranties for the PTT service. Let us recall here that this service is not supposed to support a packet loss ratio greater than 1%. In Figure 6, we present simulations results obtained after the reservation process. Thus, 20 communications are routed for the no cooperative scheme and the first level of cooperation, 14 and 6 for respectively the level 2 and 3. We compare those solutions in terms of packet loss ratio effectively observed once the flows are routed. The only viable solution under our system assumptions is the third level of cooperation that meets the QoS requirements for push-to-talk applications. To explain the phenomenon, the collisions come from inter-cooperation group communications. In the third level, the probability to have adjacent clusters belonging to different groups using the same slots is much lower as more clusters are involved in the resource sharing and thus, they use a lower amount of slots. To exemplifiying this explanation, let us consider 2 adjacent cooperation groups of 10 clusters uniformely sharing 10% of the resources. Then, 2 clusters belonging

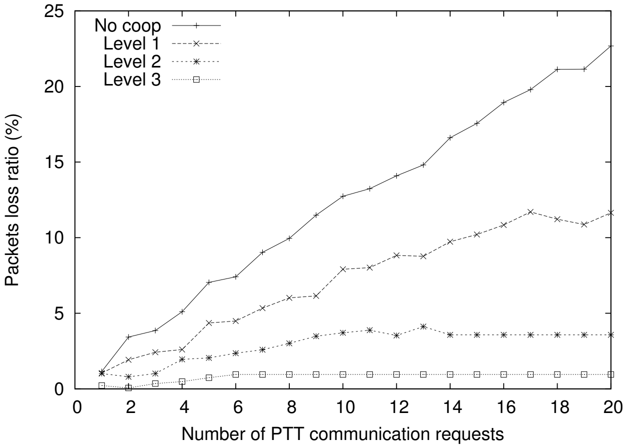


Figure 6. The figure shows the packet loss ratio for each level of cooperation.

to different cooperation groups have a probability of 10% to have the same slots assigned. On contrary, in the first level of cooperation, a group of 3 clusters sharing 30% of the resources each, the probability of collision is 3 times bigger. Of course, the traffic and cooperation groups are not that uniform in our simulation but confirms this trends.

To sum up the findings on the Push-To-Talk service in PSNs, we can conclude that this service can be supported by such a network. But due to the very stringent QoS requirements, only the third level of cooperation achieves this goal.

B. Level of cooperation performance assessment for Mail Reporting service support

In this study, we consider applications supporting delay like mail reporting services. In such services, preempting the packets is better than losing packets due to collisions. Packet loss rate may impact the entire multi-hop path while preempting the packet only delays the transmission of the information which is not an issue for mail reporting. However, QoS support is not as important as it can be for Push-To-Talk applications and can be slightly greater (we assume a tolerance of 10% of packet loss). In this study, we make the assumption that the admission control is operated within each cluster by the cluster-head and not by the Cooperation Leader. Thus, the number of accepted flows is the same for all cooperation levels. However, it is not possible to allocate the resources for every flow, especially in the third level of cooperation. Instead, the flows that cannot be scheduled immediately because of a lack of resources are delayed to next TDMA-Frame. Figure 7 shows the number of preempted packets for each level of cooperation.

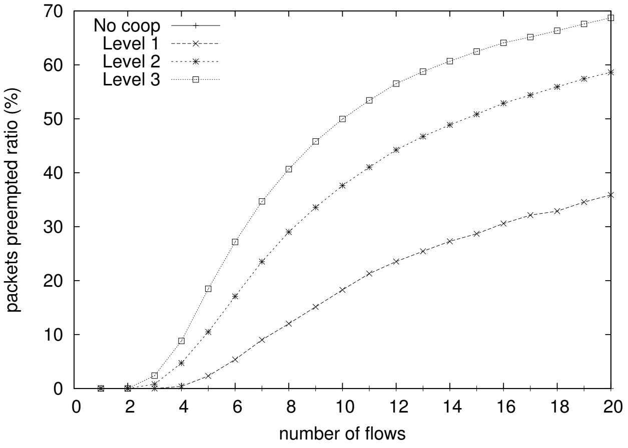


Figure 7. Percentage of preempted packets

As expected, the number of packets preempted quickly increases for the second and third level of cooperation. Since we assume a packet loss ratio of 10%, the first level of cooperation is sufficient in most cases (the packet loss ratio is similar to the one in the previous study on Push-To-Talk). while no cooperation is not suitable despite the fact that there is no packet preempted, the packet loss ratio increases too quickly.

To conclude about Mail Reporting service in PSNs, this service can be clearly supported and does not require a costly radio resource management. Mail Reporting service can easily be a viable alternative when Push-To-Talk one cannot be supported due to a lack a radio resources within the network.

V. RELATED WORK

A. Resource management

Scheduling optimization in clustered networks have been widely investigated in wireless sensors networks [7], [8], [9]. Some require specific hardware such as multiple radios or radios able to listen to several frequencies. For example, authors of [7] and [8] respectively use a combination of TDMA and FDMA/CDMA where adjacent clusters are set on distinct frequencies/codes. In [8], [9], they propose an algorithm in wireless sensor networks (WSNs) which allocates different time frames to neighboring clusters to avoid inter-cluster collisions. However, in WSNs, the sensors collect data which are sent exclusively to their cluster-head which reports the data to a base station. While in wireless ad-hoc networks, the communicating flows are random and a communication can involve any nodes of the network. Thus, the communications are not only from a member to its cluster-head, but also member to member or even inter-cluster nodes. Hence, the traffic load is varying a lot inside clusters and the slot assignment in the TDMA-Frame cannot be predetermined as it would be in a sensor network. Closer to our work [10] considers a cluster-based TDMA MAC in Ad-Hoc Networks on a single frequency but limited to the particular case of broadcasting. They make use of a technique similar to [9] by introducing super-frames cut into a predetermined number of frames. Each cluster uses a different frame to communicate with its neighbors. But as the number of frames is fixed and independent of traffic demands, this leads to a waste of slots for unloaded clusters and to starvation of loaded clusters.

B. Multi-level Hierarchies

Performances over different levels of hierarchy have been mostly studied for routing. In [11], the authors propose a routing protocol while in [12], E. Royer also provide an optimal hierarchical level for a given number of nodes. On the other side, Lian et al. [13] evaluate the update cost of routing and shows that it is acceptable until the third level of hierarchy. Those studies show that cooperation level 1, 2 and 3 can be easily integrated without generating an unacceptable number of control messages on routing issues. Moreover, they discuss about the maintenance of such cooperative schemes and justify the feasibility and viability of our proposed solutions.

VI. CONCLUSION AND FUTURE WORK

We studied the benefits of cooperative scheduling between close-by clusters in a clustered MAC. We proposed a fully distributed cooperative scheduling algorithm and evaluated its performance for two types of services. First, we showed that the third level of cooperation was the best suited for strong QoS satisfaction in push-to-talk applications. Then, we demonstrated that the first level of cooperation is sufficient to provide a good trade-off between packet loss ratio and number of preempted packets. In all cases our cooperation scheme provides much better results than a non-cooperative scheme.

One of the critical questions that this work leads to is that of the interplay between cluster formation and scheduling algorithms in a Public Safety Network. In particular in the case of a clustered MAC one would like to investigate how clustering algorithm can best help the scheduling of the packets in the network.

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