Opt-TDMA/DCR: Optimized TDMA Deterministic Collision Resolution Approach for Hard Real-Time Mobile Ad hoc Networks

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Abstract: - A new kind of critical applications, using Mobile Ad hoc networks, has appeared. These applications such as vehicular or robotic ones are called Hard Real Time Applications. Their major requirement is to respect the real time constraints especially the deadlines on the treatment and the communication delay. However, providing real-time communication, with predictable delay, is a challenge because of the Ad Hoc network features, particularly the node's mobility.

In this paper, we propose a new medium access protocol (which we call: Opt-TDMA/DCR) for these hard real time applications. Our approach consists in a distributed protocol considering dynamic network topology with mobile nodes. It is based on the TDMA protocol which we optimize by reducing the TDMA frame size. The reduction of the slot number of the TDMA frame is made with the "modulo" function which is used to select slots for transmission. However, this will probably lead to collisions between nodes selecting the same slots. Hence, a deterministic collision resolution procedure will then be applied to make communication with distinct slots. In order to verify the respect of real time constraints by our protocol, we made a communication delay analysis in the worst case and in the average case.

Key-Words: - mobile Ad Hoc networks, hard real time, TDMA, deterministic medium access protocol, communication delay

1 Introduction

Ad hoc wireless networks comprise sets of nodes connected by wireless links. The mobility of their nodes forms dynamic wireless network topologies. Those networks respond to the need of distributed and mobile applications without a fixed infrastructure. With the Ad Hoc research evolution, new application domains have been appeared such as real-time communication between mobile robots, medical wireless sensors and inter-vehicle [5]. For instance, critical safety vehicle applications need to establish hard real time communications with bounded delay between vehicles. Examples of delay critical safety applications are cooperative collision avoidance and crash warning, and abrupt obstacle avoidance [1]. In this context, communications are made between neighbor vehicles to ensure multi-hop communication with ad hoc manner. For those mobile ad hoc applications, it is not easy to ensure hard-real time requirements because of the characteristics of such networks which are decentralized and with dynamic topologies [22]. Thus, the guarantee of the real-time constraints for those critical applications is a major concern to be considered. The most important real-time constraint is the end-to-end communication delay which should not exceed the deadline, for all cases, in order to avoid catastrophic situations (e.g., vehicle collision, etc.).

For the Ad Hoc networks, the mostly used wireless technologies are IEEE 8O2.11 [12] and its enhancement IEEE 802.11p [10] which use the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) medium access protocol. This latter is a probabilistic approach which not allows to predict, in all situations, the respect of deadline on communication delay. The major problem in this issue is the use of the appropriate medium access protocol which should be deterministic allowing the communication delay prediction. The most common solution to this specific problem is to use the TDMA (Time Division Multiple Access) medium access protocol so that each node will have its separate slot time to not collide with other node communications and therefore we can easily estimate the communication delay. However, in the context of ad hoc networks especially with great number of nodes, the use of the global TDMA (a TDMA slot for each node of the network) creates a scalability problem. For that reason, most of the proposed TDMA enhanced protocols are based on dividing the TDMA frame into two main phases which are the control phase and the data phase. While the first phase is dedicated to the reservation of the slots, the second phase is dedicated for the data transmission in the reserved slots. In the control phase, some researchers propose the utilization of the contention-based methods [16, 18, 21] such as CSMA/CA, which are not deterministic. Thus, in this paper, we propose a new approach that optimize TDMA slot allocation and make deterministic communication in all phases. The optimization is made by modulo function [13] so that the TDMA frame will have a limited number of slots. In this case, a collision can be occurred from nodes having selected the same slot. Moreover, the collisions cannot be avoided in all situations especially with ad hoc mobility feature. Thus, a deterministic resolution procedure is made to get only one node transmission in a slot time. To reach real-time constraints, our proposal allows the communication delay prediction with holistic analysis [1, 2, 3] of message response times.

The remainder of the paper is organized as follows. In Section 2, we give an overview of the TDMA approaches in the literature. Section 3 describes our TDMA-based approach. Section 4 presents the mathematical analysis model for communication delay. The evaluation will be discussed in section 5 and section 6 concludes the paper.

2 TDMA Approaches in The Literature

Several TDMA based approaches are defined for Ad Hoc networks. We classify them according to the manner that TDMA slot times are allocated (Fig. 1). The major approach classes are those based on reservation phase to select the appropriate slot time for the data transmission which will be in the next TDMA phase. In the reservation phase, the medium access protocols are often probabilistic with random access (CSMA/CA, RTS/CTS, etc.) as in the wireless standard IEEE 802.11 [12]. As example of probabilistic slot reservation protocols, we have DynaMA, DTSR, RTMAC, DRAND, etc. Other approaches, as the forth Phases TDMA, are based on clustering in which cluster leader nodes are responsible for TDMA slot time allocation. Otherwise, the slot reservation can also be treated according to the elaborated routing path. This path reservation can be made relatively to the required QoS (Quality of Service) such as DDETS and RTTSA protocols. To consider the mobility features as the neighbor node’s change, some protocols have developed slot collision phase to resolve slot interference. This slot collision takes place when the same slot is assigned to different nodes which can happen if the nodes are initially far and, then move and became neighbors. Protocols of this type are ASAP, EASAP and DTSR. Finally, the class of deterministic approaches which are based on reservation phase using deterministic medium access protocol. It is designed for hard real-time communication with guaranteed delay. The ResPhase TDMA protocol is of this class. In the following, we will detail TDMA protocols to better understand the techniques used for TDMA slot reservation in Ad Hoc networks.

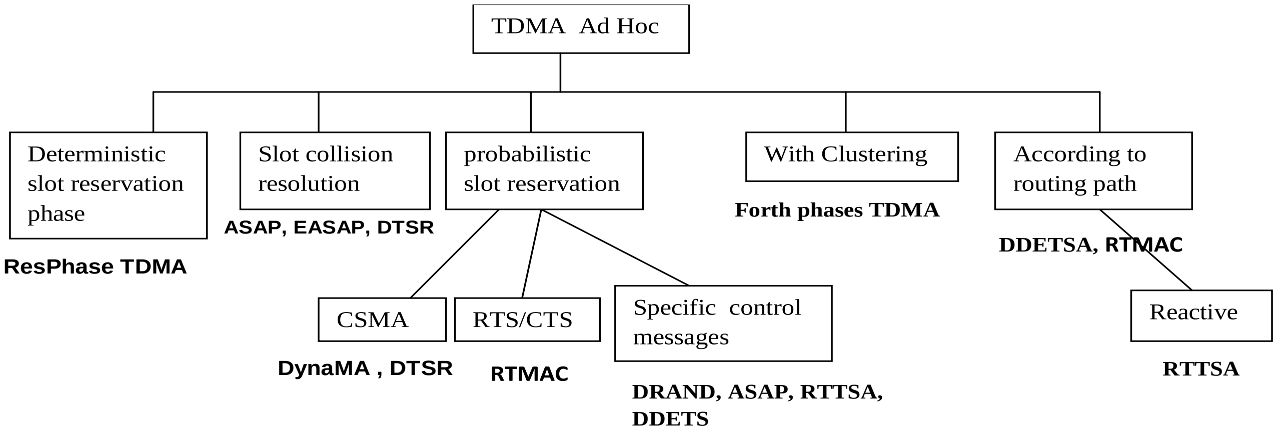

Figure .1. TDMA based approaches classification

Firstly, we present probabilistic slot reservation approaches. DRAND [11] is a TDMA reservation method which is a distributed implementation of RAND (RANDomized time slot scheduling algorithm). It is designed for a wireless network where most nodes do not move such as mesh and sensor networks. This algorithm is based on rounds which are adjusted dynamically regarding the estimates of the network delays.

DynaMAC [16] is a TDMA MAC protocol which can quickly adapt to changing topologies while guaranteeing real-time communication delay with high probability. In DynaMAC, time is divided into *cycles* (frames). The length of a cycle depends on the rate of the (CBR: Constant Based Rate) real-time traffic that is to be supported. A cycle consists of a *random phase* and a *scheduled phase*. The random phase is accessed using CSMA. It is for exchanging control data like topology information and slot allocations. The scheduled phase is accessed according to the TDMA schedule from the reserved slots in the previous phase.

In [21], the author proposes a Dynamic TDMA Slot Reservation (DTSR) Protocol which dynamically changes the frame length and the transmission schedule according to the one hop neighboring information and the bandwidth requirement. In this protocol, the frame structure consists of three parts which are the sensing window, the ATIM (Ad hoc Traffic Indication Messages) window and the communication window. The first part is used to find the free channels which can be used in the ATIM window which is the second part of the frame structure. This latter uses the IEEE 802.11 DCF mechanism to exchange control messages aiming to reserve slots in the communication window. In this third part of the frame, each time slot is used to transmit both the data packet and its acknowledgment (ACK).

Secondly, we present protocols that allocate slots according to routing paths. The RTMAC (Real Time Medium Access Protocol) [18] is a reservation protocol for real time traffic in Ad hoc networks. It consists of two components which are a MAC layer protocol and a QoS routing protocol. The medium access protocol is a real time extension of the IEEE 802.11 DCF and therefore it has a similar functioning principle. However, it includes a reservation protocol which is applied only for real-time traffic. Thus, the real time packets have their own control packets which are ResvCTS, ResvRTS and ResvACK instead of CTS (Clear To Send), RTS (Ready To Send) and ACK (Acknowledgment) used by the best-effort packets and the wait time before transmission for the ResvRTS is half the one for RTS in order to give higher priority to real time packets.

The authors in [7] propose a Distributed Dynamic End-to-end Scheduling Algorithm (DDETSA) which guarantees QoS requirements for multimedia traffic over Ad hoc networks. DDETSA is based on reserving the time slots for all the nodes in the path from the source to the destination node in such a way that multiple transmissions to the same node are assigned in different time slots in order to avoid collisions. The TDMA frame in this scheduling scheme is constructed locally in each node, basing on the received information from the neighbors.

In [9], the authors propose a Reactive TDMA Time Slot Assignment (called: RTTSA) method in which time slot assignment is performed only when wireless multi-hop transmission is initiated. Thus, they propose a reactive assignment method in which a slot is assigned to only mobile computers included in an active wireless multihop transmission route. To assign slots, control messages are used. So, a node transmits a slot request message to its follow node which replays with slot reply message to make slot reservation.

Thirdly, we present slot reservation approaches based on clustering. The approach presented in [4] (called : Forth phases TDMA) is a fully dynamic and self-stabilizing TDMA scheme based on three control phases and one data phase in which the communication is performed. For that, the time is arranged as slots and each phase has a fixed number of time slots called sub-slots. It incorporates the principle of the cluster leaders. In fact, each cluster leader is assigned a block of slots which it uses to perform tasks such as slot assignment, reclamation and re-assignment. The idea of this approach is that the leader node, which has been selected in the first phase and has obtained its own slot in the second phase, can guide the other nodes by providing feedback about the state of the slots in the third phase. Based on this feedback, the nodes can communicate their messages in the fourth and last phase.

Fourthly, we explain approaches which define a slot collision resolution phase due to mobility. ASAP (Adaptive Slot Assignment Protocol) [3] and its extension E-ASAP (Extended ASAP) [2] are a TDMA slot assignment protocol to improve the channel utilization by considering the node mobility. To obtain the slot assignment information in the contention area, a new node collects *Information packets* (noted: INFs) transmitted by its neighbors and sets its frame length as the maximum frame length among all nodes in its contention area. Then, the new node selects a slot assigned by getting an unassigned slot or doubling the frame if no unassigned slot is found. In ASAP, a collision can occur due to the conflict of slot assignment when a new node connects to equal or more than two nodes to which the same slots are assigned. However, in this situation, the new node can fail to collect the INFs due to their collisions. A retransmission of the INFs will be after waiting for randomly determined frames. This operation is repeated until the new node completes the collection of INFs from its all neighbors. So, it will get the unsigned slot for the transmission of the new node.

Finaly, we give details of protocols with deterministic slot reservation phase. In [24] and in the section five of [14], a specific TDMA approach with reservation phase (which we called: ResPhase TDMA) is proposed for the ad hoc networks. The TDMA frame is composed of two phases: the control phase and the data phase. Each node has its own slot in the control phase and it uses it to transmit the control information (the number of slots in the first phase is equal to the number of nodes in the network). In this phase, a node broadcast control message if it has a data message to send. From the broadcasted control messages, the second data phase will accordingly allocate slots for data transmission.

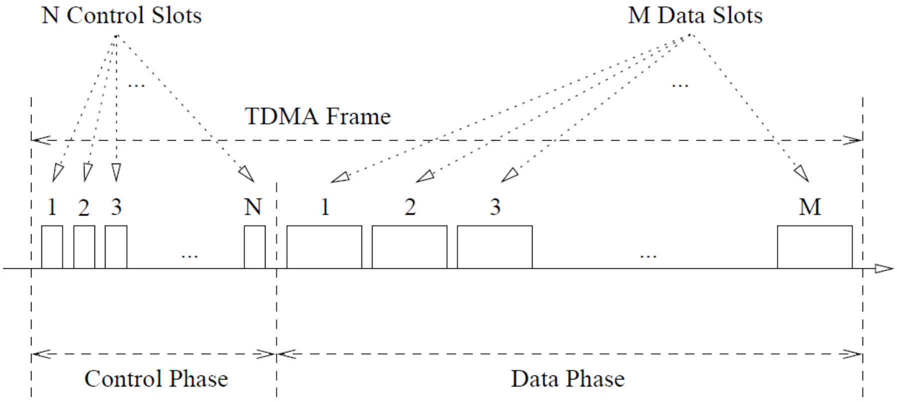

Figure.2. TDMA Frame Phases [14]

As we consider hard real-time context, the communication delay must be lower that deadline constraints. So, delay must be predicted even in the worst case. The deterministic aspect is essential to be considered in protocols to predict the communication delay. This restricts the approaches to be considered. Therefore, probabilistic slot reservation protocols are not suitable for hard real time communications because the time to transmit a message can't be known in advance for all situations. The approaches based on slot allocation, according to routing paths, are to be eliminated because we are convinced that medium access layer (or sub-layer) treatment should be separated from network layer (routing layer). In fact, medium access protocols can be applied, independently, for different routing protocols. The clustering approaches are limited for fast mobile nodes, especially, for the cluster leader which will slow-down communication delay with long time periods of making new clusters.

The pertinent approaches for hard real-time are the ones based on deterministic slot reservation phase. Moreover, the slot collision resolution approach is necessary to be considered for the mobility feature. So, from these notes, we propose a new protocol with deterministic slot reservation and slot collision resolution phase.

3 Our TDMA-Based Approach

In this section, we first present the TDMA frame size reduction approach with the modulo function. Secondly, we give an overall of our approach with the definition of the super-frame structure for different phases which are essential for transmission and collision resolution. According to the reduction of TDMA transmission frame, collisions can be occurred, so, in the third sub-section, we detail the procedure of collision resolution. In the forth sub-section, we give our protocol modeling with UML activity diagrams.

3.1 TDMA frame reduction with "modulo" function

Our approach is based on TDMA (Time Division Multiple Access) access method which is suitable for a deterministic communications. However, allocating a separate TDMA slot for each Ad hoc node in the network will lead to a large number of required TDMA slots and, therefore, the TDMA frame length will be long. Hence, we should minimize the number of slots without losing the deterministic aspect of communication.

To reduce the number of TDMA slots, we use the "modulo" function (is the remainder of the Euclidean division). In fact, the position of the TDMA slot is the result of the node's identifier "modulo" the length of the TDMA frame called "Transmission TDMA Frame". This first frame (also called: FR1) provides a data communication within a fixed number of slots called *NS1*. For that reason, nodes select their transmission slot times, of the first TDMA frame "FR1", according to the result of the "modulo" formula (1).

$$NSlot_i = N_i \bmod NS_1 \qquad (1)$$

With *mod* is the modulo operator where *a mod n* is the remainder of the Euclidean division of *a* by *n*, NS_1 is the number of slots in the first TDMA frame (Transmission TDMA Frame), N_i is the node identifier (logical number) and $NSlot_i$ is the position of the selected slot for the node *i* in the first Frame. For example, if a node has an identifier number which is equal to 95 ($N_i=95$) and if the number of slots in the first frame (with length NS_1) is equal to 10, we will get a slot time position which is equal to 5 (from equation 1, we have: $5 = 95 \bmod 10$) for this node.

The selection of the slot time with the "modulo" function will lead to reduce the TDMA frame length and get a scalable value of the TDMA slots number. However, this can lead to make collision if two nodes get the same result value of the "modulo" function. For example, if the nodes have the respective identifier numbers 95 and 5 with NS1 equal 10, they will get the same slot time value 5 which will cause collision.

3.2 The OPT-TDMA/DCR super-frame structure

While the TDMA communication using the "modulo" function (OPT-TDMA/DCR) reduces the communication delay and allows the nodes to select different slots, it is not completely free of collision. This issue should be resolved, especially for hard real time communications. For that reason, in the case of collisions, we add a second TDMA frame in order to resolve them. This additional frame consists of so many sub-frames which are the "access" sub-frame, the "End Of Frame" sub-frame and the "Resolution Collision" sub-frames whose number is equal to the number of the occurred collisions in the Transmission frame. While the access sub-frame allows the colliding nodes to inform each other about their collisions and the appropriate order, the "End Of Frame" marks the end of resolution of collisions and, therefore, the end of the TDMA super-frame.

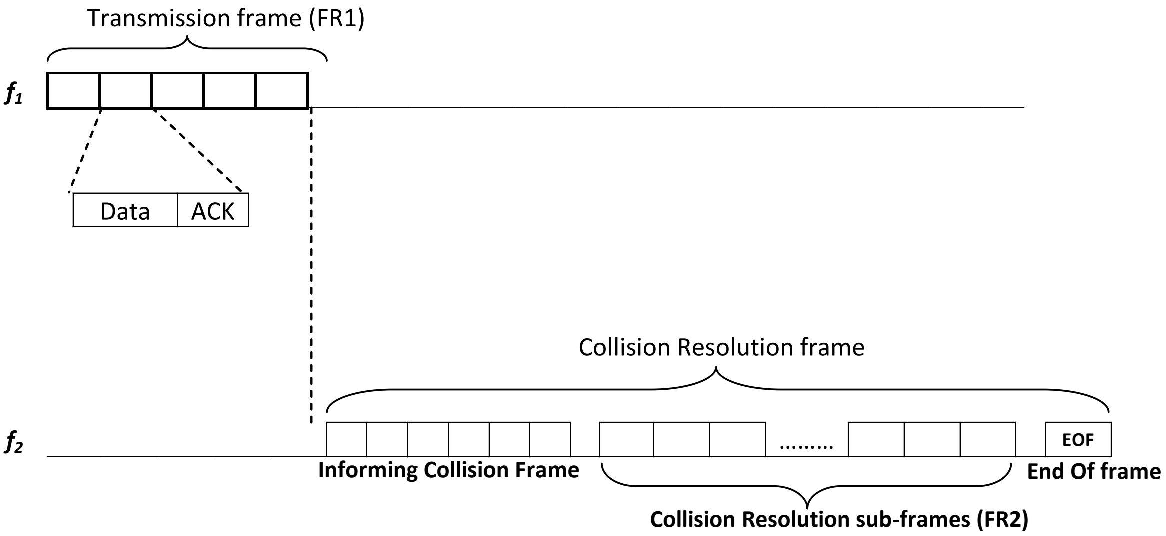

Figure .3. The Opt-TDMA/DCR super-frame structure

Since the number of the "Collision Resolution" sub-frames is variable and, therefore, the TDMA super-frame length is not constant, we will have a synchronization problem. For that reason, we use two frequency values and further two waiting queues. The first frequency (noted: *f1*) is used for the transmission TDMA frame and the second frequency (noted: *f2*) is used to resolve the occurred collisions by the second TDMA frame. The obtained TDMA super-frame structure is presented in Fig.3.

3.3 Collision Detection and resolution

In the wireless networks, unlike the wired ones, we cannot implement a direct mechanism to detect collisions. Thus, we should use the acknowledgment in order to check if the communication between the source and the destination has been achieved without collisions. In fact, if a transmitter does not receive an acknowledgment, it considers that a collision has been occurred. For that reason, each slot time is divided into two sub-slots. The first one is used to transmit data and the second to send back the acknowledgement (Figure 2). Thus, if we have sent data in the first sub-slot without receiving an acknowledgement in the second sub-slot of the same slot, we conclude that a collision has been occurred. In this case, we apply *a collision resolution procedure* which will be described in the following subsections.

3.3.1 A single collision resolution Procedure

In the first TDMA frame (Transmission Frame), the nodes, which have to send data, select the time slot to send according to the "modulo" formula (1). However, a collision can happen if two nodes obtain the same formula result and, therefore, send their messages in the same slot. In this case, we add a second TDMA frame (called: TDMA Collision Resolution Frame) in the same TDMA super frame as shown in figure 4.

In the TDMA Collision Resolution Frame, the nodes in collision should select other different slots. This can be provided if we change the value of the number of slots NS_1 by another value NS_2 in the Equation (1). For that, the second TDMA frame will have NS_2 slots instead of NS_1 for the first frame.

For example, the nodes having respectively the identifiers 95 and 5, which got the same result of the slot position (5) with $NS_1=10$, can select a different slots if we consider $NS_2=11$ instead of $NS_1=10$. In fact, the first node will obtain the slot "7" (95 *mod* 11) as result from Eq. (1) and the second node will obtain the slot "5" (5 *mod* 11). So, the collision will be resolved.

In order to select the appropriate TDMA Collision Resolution frame length (NS_2**),** which avoids that the collision takes place again, we consider the properties 1 and 2. The selected slot time in the Collision Resolution frame is with modulo function as Eq. (1). However, in the second frame, we consider different TDMA frame length (NS_2) to get different selected slot times from the first frame.

Property 1: A collision takes place if at least two nodes N_i and N_j obtain the same result of the "modulo" formula (1), as shown in the following formula:

$$N_i \bmod NS_1 = N_j \bmod NS_1 \qquad (2)$$

Property 2: If a collision happens between two nodes in the first frame (Transmission Frame)**,** it will be resolved by the second frame (called: Collision Resolution frame) verifying the conditions of the following equation:

$$NS_1 \cdot NS_2 > N \text{ and } GCD(NS_1, NS_2) = 1 \qquad (3)$$

With GCD function is the Greatest Common Divisor, N is the number of nodes (the node identifier (N_i) vary from 1 to N), NS_1 is the number of slots (Frame length) of the first frame and NS_2 is the number of slots (Frame length) of the second frame.

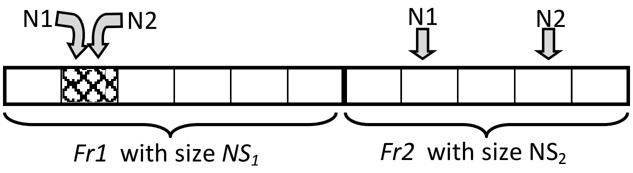

Figure.4. Single collision resolution procedure

Proof:

We make a proof by contradiction, *so* we assume that a collision takes place in the first (size NS1) and in the second (size NS2) frames for the nodes Ni and Nj. Thus from the property 1:

$N_i \bmod NS_1 = N_j \bmod NS_1$ and

$N_i \bmod NS_2 = N_j \bmod NS_2$

=> $N_i - NS_1 \cdot Q_1 = N_j - NS_1 \cdot Q_2$ and $N_i - NS_2 \cdot Q_3 = N_j - NS_2 \cdot Q_4$, where Q_1, Q_2, Q_3

et Q_4 are the quotients of the Euclidean divisions respectively of N_i by NS_1, N_j by NS_1 , N_i by NS_2 and N_j by NS_2.

$$=> \begin{cases} N_i - N_j = NS_1 \cdot (Q_1 - Q_2) \\ N_i - N_j = NS_2 \cdot (Q_3 - Q_4) \end{cases},$$

so: $(N_i - N_j)$ is multiple of NS_1 and NS_2.

From the property 2, we have $GCD(NS_1, NS_2) = 1$. Thus:

$(N_i - N_j) = NS_1 \cdot NS_2 \cdot B$, $B \in Z$. Also, from the same property 2, we have $NS_1 \cdot NS_2 > N$, so: $(N_i - N_j) > N$ which is not correct because the logical identifier of the node is lower than the number of nodes: $N_i < N$ and $N_j < N$ $\Rightarrow (N_i - N_j) < N$. From this contradiction, the initial assumption is not correct. So, we conclude that if a collision takes place in the first frame, it will not be in the second frame which we called a collision resolution frame. □

<u>Property 3 (Generalization of Property 2):</u> In the case that the collision takes place between more than two nodes in the same slot. The issue will be resolved in the second TDMA frame (Same reasoning as in property 2).

If a collision happened in one slot from the first TDMA frame, we are sure that it will not happen in the second TDMA frame. However, if a collision happens in more than one slot time, we cannot be sure that the second TDMA frame resolves the issue, as shown in the fig.5. In fact, we consider the case in which the node N_1 and the node N_2 have selected the same slot in the first TDMA frame of the TDMA super-frame, and at the same time, the nodes N_3 and N_4 have also selected the same slot. In the second TDMA frame, the nodes N_1 and N_3 can select the same slot. Thus, a collision will happen again. In such cases and as a general collision resolution problem, we define *a multiple collision resolution procedure*.

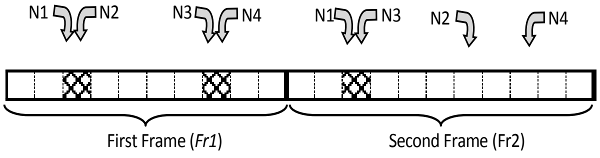

Figure.5. The case of two different collisions in the same TDMA frame

3.3.2 A single collision resolution Procedure

For the problem of multiple collisions in the first TDMA frame, we propose to solve the happened collisions consecutively. Thus, in the second TDMA frame (Collision Resolution TDMA frame), we define a TDMA sub-frame for each collision resolution as to consider a single collision resolution at each time. So, in Fig. 6, the first collision (C_1) between N_1 and N_2 will be resolved at the first sub-frame of the TDMA resolution frame. Then, the second sub-frame will resolve the collision (C_2) between N_3 and N_4.

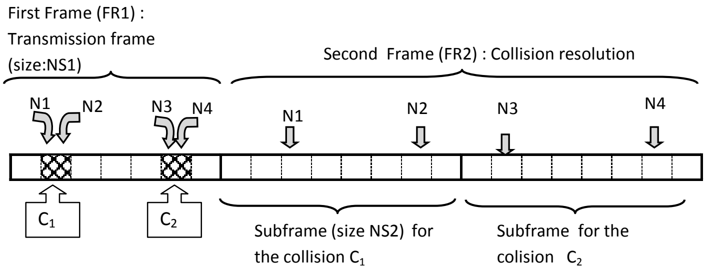

Figure.6. Multiple collision resolution procedure

4 Mathematical analysis model

In this section, we use a holistic analysis [15, 17, 19, 20, 23] in order to determine the response time (noted: R_i) of the traffics. The response time is the accumulation of the waiting time in the queue (noted: W_i) and the service time (noted C_i). Hence:

$$R_i = C_i + W_i \quad (4)$$

In a network, a message m_i waits in the queue during W_i and then will be transmitted according to medium access protocol during of a C_i time. In order to calculate the waiting time of a message m_i, we assume that we can predict the number of messages of each traffic which comes in the queue before the current message m_i.

As we consider worst case analysis for real-time communications, we rely on the assumption of theorem 6 in the well known work by Liu [6]. In this case, the waiting time of a message m_i, which comes at the instant t, depends on the service time of the previous messages which are already in the queue. For that reason, we try to predict the number of messages of the traffic j (noted : $N_j(t)$) which will be served before the message m_i. Moreover, this message is also delayed by the messages of its type of traffic having the number $N^*_i(t)$. So, we define the waiting time of the message m_i at the instant t ($W_i(t)$) as the cumulative workload for the previous traffics. Thus,

$$W_i(t) = \sum\nolimits_{j \in msg, j \neq i} N_j(t) \cdot C_j + N_i^*(t) \cdot C_i \quad (5)$$

With *msg* is the set of traffic, C_j is the service (transmission) time of a message from the traffic *j* and $W_i(t)$ is a sequence which converges when $W_i(t) = t$ [15]. At this instant, we can conclude that the sequence converges and the *Cumulative Workload* is finished. This instant is the instant in which we have no longer messages in the queue before the message m_i and, therefore, the message will be served.

4.1 General Formula of response time in OPT-TDMA/DCR

Our medium access method consists of 2 frames (Transmission frame and Collision Resolution frame) which are successively handled with two independent frequencies. So, our model consists of two queues (fig. 9). The first one is considered for the transmission frame and the second queue is for the collision resolution frame.

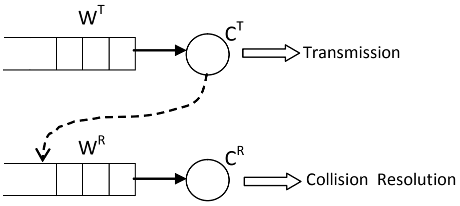

Figure.9. Queue model

According to this modelling, the response time of the traffic *i* is given by the following formula:

$$R_i = R_i^T + R_i^R \quad (7)$$

With R_i^T is the response time in the transmission frame and R_i^R is the response time in the collision resolution frame. In each queue, we apply the same analytical model as Equation 4. So,

$$\begin{cases} R_i^T = C_i^T + W_i^T \\ R_i^R = C_i^R + W_i^R \end{cases} \quad (8)$$

With C_i^T is the transmission (service) time in the transmission frame, W_i^T is the waiting time in the queue in the transmission frame, C_i^R is the transmission (service) time in the Collision Resolution frame and W_i^R is the waiting time in the queue in the Collision Resolution frame.

In the next sections, we will determine the waiting times and transmission times in the worst case and in the average case.

4.2 Transmission time in the worst case

Since, we use the TDMA based medium access method in the transmission frame; in the worst case, a node waits for a whole transmission frame to get its transmission slot. So, the transmission time C_i^T is equal to:

$$C_i^T = NS_1 \cdot t_{slotm} \quad (9)$$

With t_{slotm} is the TDMA slot time to transmit a full message and NS_1 is the number of slots in the TDMA transmission frame.

To compute the transmission time in the Collision Resolution frame (C_i^R), firstly, we must predict the number of Collision Resolution sub-frames. Secondly, we compute the sizes of the *Informing Collision Frame* and the *End Of Frame* (See Fig. 3).

We assume that the node N_i has N_v^i neighbors. The maximum number of collisions is obtained when the nodes cause more collisions which take place separately by every two nodes. In this case, we will have the maximum number of collisions Nb^i_{col} which is the half of the number of neighbors, as shown in equation 10.

$$Nb_{col}^i = \left\lfloor \frac{N_v^i}{2} \right\rfloor \quad (10)$$

In this case, the Collision Resolution sub-frame *FR2* (with NS_2 slots) will be repeated Nb^i_{col} times for each collision. So, it takes ($NS_2 \times Nb^i_{col}$) slot times. Furthermore, we must consider the informing collision frame with NS_1 slots and the end of frame with NS_1 slots. So, the transmission time in the frame *FR2* (C_i^R) for the node *i*, in the worst case, is given by the equation 11.

$$C_i^R = (NS_2 \cdot Nb_{col}^i) \cdot t_{slotm} + (2 \cdot NS_1) \cdot t_{slotA} \quad (11)$$

With t_{slotm} is the TDMA slot time to transmit a full message and t_{slotA} is the TDMA slot time to transmit a *JAM* message for the informing collision frame and the TDMA silent slots for the end of frame.

4.3 Average transmission time according to the probability of collision

In order to determine the average value of the response time R_i (from equation 8), we should compute the values of the transmission times C_i^T and C_i^R as well as the values of the response time W_i^T and W_i^R.

The average value of the transmission time in the transmission frame (C_i^T) is given by the half of the

TDMA frame size which represents the average of selected slot. So:

$$C_i^T = \left(\frac{NS_1}{2}\right) \cdot t_{slotm} \tag{12}$$

With t_{slotm} is the TDMA slot time to transmit a full message.

The average value of the transmission time in the collision resolution frame is noted C_i^R. If we consider that we have j nodes in collision, the collision resolution of the message m_i will be after $C_i^R(j\ coll)$. In fact, we have the Informing Collision Frame with ($NS_1 \times t_{slotA}$) followed by j collision resolution sub-frames (The collisions are resolved one by one) with the size value of NS_2. Since we talk about the average case, the collision resolution and the transmission of the message will be after $(NS_2 \times j)/2$ slots. Hence:

$$\begin{cases} j \neq 0,\ C_i^R(j\ coll) = NS_1 \cdot t_{slotA} + \left(\frac{NS_2 \cdot j}{2}\right) \cdot t_{slotm} \\ C_i^R(0\ \text{coll}) = 0 \end{cases} \tag{13}$$

In the case of *0* collisions, the collision resolution phase is not invoked. For that reason, the transmission time of this phase is null ($C_i^R(0\ coll)=0$). The collision resolution time C_i^R of the message m_i is determined according to the number of nodes in collision. This number is limited by the number of neighbours N_v. Relative to the probability of collision $P(j\ coll)$ between j nodes, the average value of C_i^R will be computed by the following:

$$C_i^R = \sum_{j=0,\, j\neq 1}^{N_V} P(j\ coll) \cdot C_i^R(j\ coll) \tag{14}$$

<u>Lemma:</u> Probability to have collisions between j nodes in a neighbourhood of N_v nodes for a TDMA frame having NS_1 slots:

$$p(coll\ between\ j\ nodes) = \frac{C_{N_V}^{j} \cdot NSS(\min(\lfloor \frac{j}{2} \rfloor, NS_1)}{\sum_{k=2}^{N_V} C_{N_V}^{k} \cdot NSS(\min(\lfloor \frac{k}{2} \rfloor, NS_1) + A_{NS_1}^{N_V} \cdot \delta(NS_1 - N_V)} \tag{15}$$

With $\begin{cases} \delta(x) = 0\ if\ x < 0 \\ \delta(x) = 1\ if\ x \geq 0 \end{cases}$, and $NSS(k) = \sum_{l=1}^{k} C_{NS_1}^{l}$.

With $C_{N_V}^{j}$ is the combination which computes the number of ways of picking j unordered outcomes from N_V possibilities. $A_{NS_1}^{N_V}$ is the arrangement which computes the number of ways of picking N_v ordered outcomes from NS_1 possibilities. *NSS(K)* is the number of possibility to select k slots among NS_1.

Proof:

Firstly, we proof the *NSS(k)* expression used in the global formula (equation 15). So, to select k slots among NS_1 ones, we use the combination $C_{NS_V}^{l}$ and we vary l from 1 to k so that we consider all the possibilities until the maximum number k. Thus, the possibility to select k slots among NS_1 ones is given by the following formula: $NSS(k) = \sum_{l=1}^{k} C_{NS_1}^{l}$.

Then, the probability of j nodes in collision (equation 15) is, by definition, equal to the number of the possibilities that j nodes are in collision when allocating the slots ($term_1$) divided by the total number of all possibilities of collisions when allocating the slots ($term_2$). So: $p(coll\ between\ j\ nodes) = \frac{term_1}{term_2}$. We start by proving ($term_1$), then we will prove ($term_2$).

- Proof of ($term_1$) :

If we consider j nodes in collision, we have $C_{N_V}^{j} \cdot NSS(\min(\lfloor \frac{j}{2} \rfloor, NS_1)$ possibilities of the slots allocation. Indeed, we firstly select j nodes to be in collision among the set of neighbours having the cardinality N_v (which gives $C_{N_V}^{j}$). Secondly, for each selected node, we search for the slots in which we can have j nodes in collision. The number of the selected slots of the collisions is equal at most to $\lfloor \frac{j}{2} \rfloor$ (since each collision requires at least 2 nodes in collision). Furthermore, this number cannot exceed the number of the slots N_1 of the frame. Hence, the number of the possibilities that we select slots with j collisions is equal to $NSS(\min(\lfloor \frac{j}{2} \rfloor, NS_1)$.

- Proof of ($term_2$):

We should search for all the possibilities of the slots allocation relative to collisions. Thus, we can have from 0 to N_V possible nodes with collisions. For 0 collisions, we should select N_1 different slots for each node in the set of neighbours (N_V) which gives $A_{NS_1}^{N_V}$. Moreover, we should assume that $NS_1 \geq N_V$. Otherwise, the consideration of 0 collisions is not possible because some nodes will necessary select the same slot. Hence, we obtain the following expression: $A_{NS_1}^{N_V} \cdot \delta(NS_1 - N_V)$. We should also consider, in *term₂*, the possibilities of 2 until N_V nodes in collision. Thus, we will have (like in *term₁*) the following expression: $\sum_{k=2}^{N_V} C_{N_V}^{k} \cdot NSS(\min(\lfloor \frac{k}{2} \rfloor, NS_1)$. Hence, we obtain the equation 15 of the lemma with the proof of the expressions *term₁* and *term₂*. □

4.4 Waiting time

To determine W_i^R and W_i^T, we refer to the mathematical model of the section 4.1 . The waiting times of the transmission frame (W_i^T) and the Collision Resolution frame (W_i^R) are determined by the Equation 5. Thus:

$$W_i^T(t) = \sum_{j \in msg, j \neq i} N_j^T(t) \cdot C_j^T + N_i^{T*}(t) \cdot C_i^T \quad ,$$

$$W_i^R(t) = \sum_{j \in msg, j \neq i} N_j^R(t) \cdot C_j^R + N_i^{R*}(t) \cdot C_i^R \tag{16}$$

During the transmission frame, we assume that the traffic arrivals are periodic (T_i is the inter-arrival period of the traffic *i*). The calculation of the number of arrivals N_j^T and N_i^{T*} is presented as in equation 6.

However, the arrivals in the queue of the Collision Resolution (W_i^R) are not periodic because of the delay caused by the transmission queue which injects the outgoing traffic (Fig. 8). The average period of the inter-arrivals of the traffic *i* (noted: T_i') depends on the first queue. In fact, in the case of collision ($p(coll.) = 1 - p(no\,coll.)$), the outgoing traffic from the transmission queue will be injected in the second queue of the Collision Resolution with a delay which does not exceed the time period T_i. Thus, the minimum value of T_i' is T_i. This inter-arrival period will be multiplied each time ($k*T_i$) if there is no collision ($p^k(no\,coll.)$). Indeed, without collision, we have not outgoing traffic from the first queue (Fig. 8). Thus:

$$\begin{aligned} T_i^{'} = \quad & 1 - p(no\ coll.) \quad \cdot T_i \quad + \\ & \sum_{k=1}^{\infty} k \cdot T_i \cdot p^k(no\ coll.) \end{aligned} \tag{17}$$

With $p(no\,coll.)$ the probability that we have not collisions between nodes in the neighbourhood of N_v nodes in the transmission frame (NS_1 slots). So:

$$p(no\,coll.) = \frac{NS_1}{NS_1^{N_V}} \tag{18}$$

5 Evaluation

Our approach are evaluated by simulation based on the presented formulas, we will compare it with two other major approaches which are the global TDMA approach and the TDMA approach with the reservation phase [14]. In this comparison, we consider the variation of the delay according to the number of nodes in the network in one hand and the packet size in the other hand. Then, we will analyze the end-to end delay given by our protocol Opt-TDMA/DCR when varying the ratio between frame sizes NS_1 and NS_2 associated respectively to transmission frame and collision resolution frames.

While the worst case is more interesting when talking about the hard real time communications, we will consider also the average case since it gives us an idea about the communication delay in most of the time.

Thus, this section is divided in three principle subsections which are the comparison of the communication delay in the worst case, the comparison of the communication delay in the average case and the comparison according to the frames length.

5.1 Comparison between Opt-TDMA/DCR and the other approaches in the worst case

We start by giving the delay formulas for each approach (Global TDMA, TDMA with reservation phase and Opt-TDMA/DCR) in the worst case. Then, we present the comparison of the delay using these approaches.

5.1.2. Comparison according to the number of nodes in the network

In this section, we aim to compare the end-to-end delay of our approach and the other ones according to the number of nodes in the Ad hoc network. Hence, we consider that the number of neighbors is equal to *5* and we vary the total number of nodes in the network. We note that we vary frame lengths *NS1* and *NS2* with the total number of nodes *N* such as $NS_1 = \lfloor \sqrt{N} + 1$ and $NS_2 = \lfloor \sqrt{N}$ according to the property 1**.** The obtained results are represented in Fig. 10.

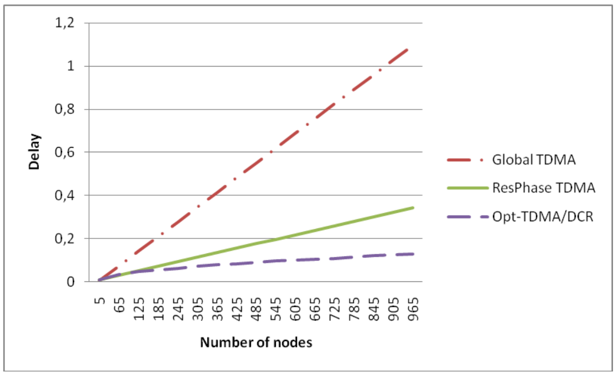

Figure.10. Comparison in the worst case according to the number of nodes

We observe that the delay offered by our approach Opt-TDMA/DCR is lower than the delay offered by the other approaches, except for small networks with less than 65 nodes in which The TDMA approach with a reservation phase offers a lower delay. Thus, in a small network, for “ResPhase TDMA”, a reservation phase is too small so that most of the bandwidth is used to transmit data.

The effectiveness of our approach reveals itself most vividly in the case of a large number of nodes in the Ad hoc network. For small networks, the benefit of our Opt-TDMA/DCR approach is not justified in the worst case because it presents additional frames if there are collisions. However, the interest of our approach for this kind of networks looks better in the average case (see section 4.2).

5.1.3. Comparison according to the number of neighbors

We want to confirm the previous results about the delay with varying the number of neighbours in the network. Hence, we consider that the total number of nodes is equal to 225 (frame sizes are: NS_1=17, NS_2=6). We vary the number of neighbours, so the results are represented in Fig 11.

Figure 11 shows that Opt-TDMA/DCR offers a lower delay when the maximum number of neighbors is lower than 23 relatively to the total of 225 nodes. We can conclude that in most realistic cases, it performs interesting results.

In the general case, our approach reduces the number of the reserved transmission slots compared to the other approaches. This affects the communication delay in the network having a large number of nodes. Thus, the effectiveness of our approach reveals itself if a number of neighbors is much lower than the number of nodes in the network. Indeed, the transmission frame is followed by a collision resolution frame that will be of lower size especially if the number of collisions is low. Therefore, the number of collisions depends itself on the number of neighbours.

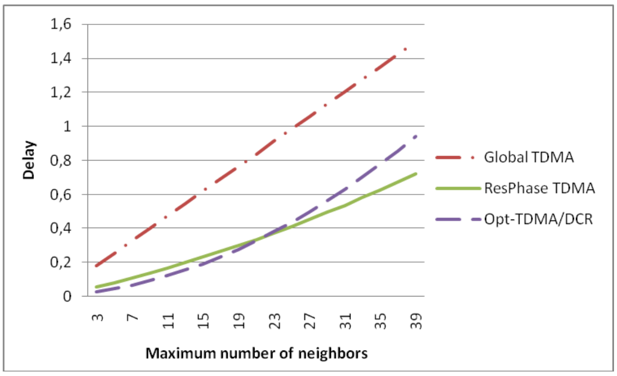

Figure.11. Comparison according to the number of neighbors in the worst case

5.1.4. Comparison according to packet size

In this section, we aim to study the impact of the packet size on the effectiveness of our approach. Hence, we consider that the total number of nodes is equal to 361 (frame sizes are: NS_1=20, NS_2=19), the number of neighbours is equal to 5 and we vary the packet size (consequently the transmission time slot t_{slotm}). The obtained results are represented in Fig.12.

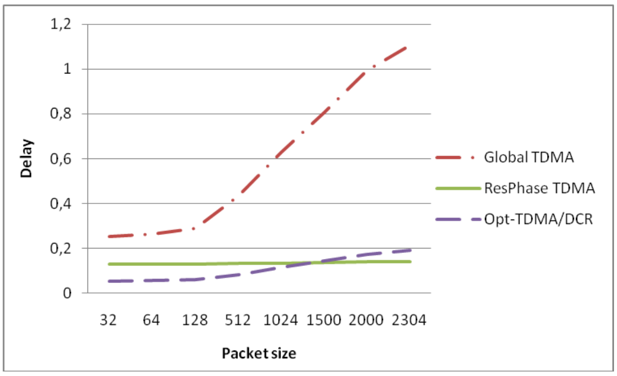

Figure.12. Comparison in the worst case according to the packet size

We observe that Opt-TDMA/DCR offers a better delay when a packet size is lower than 1024 bytes. In fact, the collision resolution frame (FR2) in our approach (Opt-TDMA/DCR) is more influential since we adjust the slot time according to the packet size. Thus, when a packet size exceeds 1024, the ResPhase TDMA method offers a better delay. However, in real context of real time traffic, it is realistic to get packets length less than 1024 bytes.

The TDMA approaches having a reservation phase appear interesting for packets having a large size. In that case, the reservation phase used in such approaches will be relatively low comparing with the transmission phase. In the opposite case, for packets size lower than 1024 bytes, our approach offers best delay results. Moreover, as much the packet size is low as the communication delay is interesting. For hard real time applications, in particular for industrial ones, the messages have most of the time a low size.

In this section, we compared the delay between our approach and the other approaches in the worst case which is very important for hard real time traffic. The results show that OPT-TDMA/DCR gives better communication delay values.

However, the worst case happens rarely and most of the time, the network doesn't attend these results. For that reason, it would be interesting to compare them also in the average case.

5.2 Comparison in the average case

5.2.1 Comparison according to the number of nodes in the network

We consider the same simulation parameters as the previous section. We vary the total number of nodes of the network and we observe the resulting delay (Fig. 12). We select the frame sizes NS_1 and NS_2 according to the total node number N such as: $NS_1 = \left\lfloor \sqrt{N} \right\rfloor + 1$ and $NS_2 = \left\lfloor \sqrt{N} \right\rfloor$.

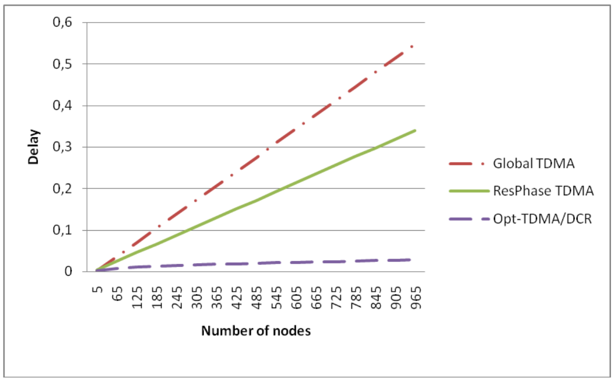

Figure.13. Comparison in the average case according to the number of nodes

We observe that the average delay offered by our approach (Opt-TDMA/DCR) is considerably lower and more stable than the other approaches. Moreover, more the number of nodes increases in the Ad hoc network, more our approach offers a better delay results compared to the other approaches in which the delay increases significantly. This is due to the reduction of the number of slots in the transmission frame (*FR1*) which consequently reduces the delay.

5.2.2 Comparison according to the number of neighbors

In this section, we consider that the total number of nodes is equal to 225 and frame sizes NS_1=17 and NS_2=6. We vary the maximum number of neighbours. The obtained results are represented in Fig. 14.

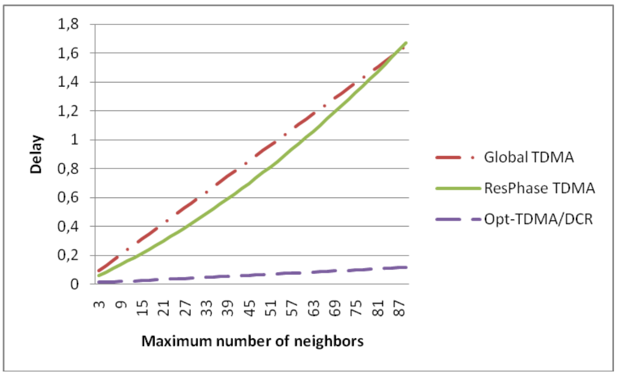

Figure.14. Comparison in the average case according to the number of neighbors

Even by varying the maximum number of neighbours, until 87, our approach stays interesting. The increasing of the delay according to the number of nodes is notably lower than the other approaches (The slope is higher for the other approaches).

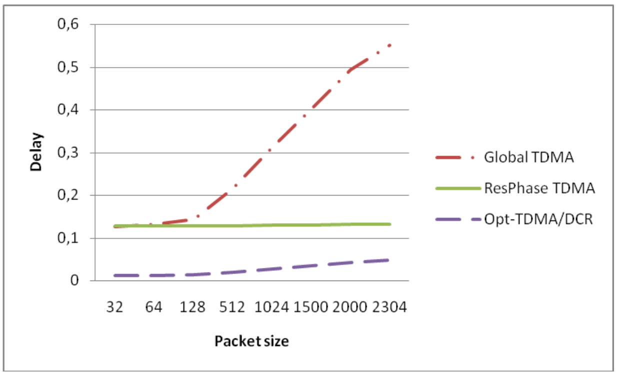

Figure.15. Comparison in the average case according to the packet size

5.2.3 Comparison according to packet size

We consider that the total number of nodes is equal to 361 and frame sizes NS_1=20 and NS_2=*19*. We vary the value of the packet size (the transmission time slot t_{slotm}). The obtained results are represented in Fig.15. In all situations, unlike the worst case, Opt-TDMA/DCR offers a better delay which is notably lower and more stable than the other approaches, regardless of the packet size and the time slot values.

6 Conclusion

The Hard real-time communication over Ad Hoc networks has got a lot of attentions recently. The researchers focus, especially, on the guarantee of the end-to-end delay since it is the most important requirement for the real-time applications. This is not an easy task because of the possibility of collision. In this paper, we have proposed an Optimized TDMA Deterministic Collision Resolution Approach for Hard Real-Time Mobile Ad hoc Networks (Opt-TDMA/DCR) which is based on the TDMA medium access method. In order to select the TDMA slots, we use the “modulo” operator. However, a collision can occur even when using this TDMA method. Hence, we resolve this issue deterministically by using a Collision Resolution Frame which is, a TDMA sub-frame, used only in the case of collisions in order to resolve them. For the real-time constraint validation, we give mathematical analysis which predicts the communication response time.

We have evaluated our approach by comparing it with the other ones which are the global TDMA and the TDMA using a reservation phase. We have started by comparing the end-to-end delay in the worst case since our approach is dedicated for the Hard Real Time applications. The results showed that our approach is more affective in the case of a large number of nodes for the Ad Hoc networks. However, the worst case occurs rarely and in most of the time we have different end-to-end delay values. For that reason, we have also compared our approach with the others, in the average case, which give us an idea about the frequent delay values. The results showed that our approach offers a lower communication delay.

Thus in all cases, we conclude that our proposed medium access protocol Opt-TDMA/DCR offers lower communication latency and it gives a predictable time analysis which is the most critical requirement for the Hard Real Time applications. Hence, it is very interesting for this kind of applications.

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