A Two-Phase Contention Window Control Scheme for Decentralized Wireless Networks

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Abstract—**Most studies on performance of IEEE 802.11 distributed coordination function (DCF) have proved that the binary exponential backoff (BEB) algorithm suffers from low throughput, long transmission delays and low transmission reliability, for a high traffic load. In this paper, we propose a two-phase contention window (TPCW) access mechanism that enhances the aggregate throughput and transmission reliability while decreasing the medium access delay. In addition, this scheme aims at being computationally simple. This work characterizes the performance of the TPCW mechanism for different parameterization values. An analytical model is proposed for the TPCW access mechanism, which characterizes the frame transmission reliability, the total transmission delay and the aggregate throughput. The validity of our analytical model is verified through extensive simulations. By comparing the performance results, we conclude that the proposed scheme can significantly enhance IEEE 802.11 in terms of frame transmission reliability, total transmission delay and aggregate throughput.** [1]

I. INTRODUCTION

In the recent years, several algorithms have been proposed to improve the performance of decentralized wireless networks. The set of performance metrics characterized in wireless communications usually include the network's throughput, along with the transmission delay and reliability. In this paper, we propose a two-phase contention window (TPCW) mechanism, which can achieve higher aggregate throughput performance along with low transmissions' delay and high reliability. The contention mechanism is composed by two different contention stages, which aims at decreasing the number of nodes that effectively compete for the channel, improving the scalability of the protocol when a higher number of competing nodes is considered. The proposed mechanism was inspired in the scheduled channel polling (SCP) [1] and cascading tournament [2] medium access control (MAC) protocols proposed for wireless sensor networks (WSNs).

The cascading tournament MAC [2] (CT-MAC) protocol is based on the SCP and is intended for the WSNs. It relies on cascading iterations of tournaments jointly with static allocation of time slots to nodes that want to contend for the channel and considers two contention windows. Differently from [1] and [2], and to the best of our knowledge, no work has addressed an analytical formulation of a TPCW scheme, which is proposed in this work and characterized for several network performance metrics. Extensive simulations validate the proposed theoretical analysis for the transmission reliability, total transmission delay and aggregate throughput. Finally, the performance results achieved with TPCW confirm that such a two-phase contention scheme is particularly intended for high nodes' density scenarios, where the number of competing nodes can be too high.

The main contributions are the following: the proposal of the TPCW access mechanism, which is intended to increase the aggregate throughput and access reliability while decreasing the medium access delay; the derivation of an analytical model for the TPCW access mechanism, which characterizes the frame transmission reliability, the medium access delay and aggregate throughput; a comparative characterization of TPCW's performance through simulation.

The remainder of this paper is organized as follows. Section II addresses the related work for the random access (RA) algorithms used in decentralized wireless networks. Section III describes the proposed mechanism for the collision resolution in which an analytical model for the two-phase contention window mechanism is proposed. In addition, the performance metrics assumed in this work are defined and discussed. Section IV presents and analyzes the simulation results for the frame transmission reliability, total transmission delay and aggregate throughput performance metrics in comparison with the IEEE 802.11 distributed coordination function (DCF). Section V concludes the paper.

II. RELATED WORK

The regulation of the contention period in decentralized medium access control schemes has been a topic of high interest for many years. RA algorithms (e.g. [3]–[7]) usually adopt slotted time-domain and unit-sized packets in a common control channel. These algorithms use successful transmissions

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or busyness of the channel as an indirect measure of the number of competing nodes, which is employed to regulate the randomized medium access of each node.

The most successful RA algorithms used in decentralized wireless networks are contention-based ones. In contention-based MAC schemes, the time is divided into consecutive slots, and the nodes are able to sense the channel. Each node adopts an initial medium access probability, which is determined by its contention window (CW). A given number of slots (randomly chosen from the interval $[1, \; CW]$) is assigned to a contention counter, representing the number of slots to be sensed before accessing to the channel. A collision occurs if at least two nodes access the channel in the same slot. Otherwise, the transmission succeeds. RA algorithms can be based on simple heuristics. One of the most popular heuristic RA algorithm is the exponential backoff adopted in the IEEE 802.11 standard [3], which is based on the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. From the huge amount of heuristic RA algorithms described in the literature [4], we highlight the *"gentle distributed coordination function"* (GDCF) [5], because of its performance in terms of throughput. While in IEEE 802.11 a node sharply cuts the CW after a successful transmission and independently of the number of nodes accessing the channel, GDCF adopts a more conservative approach: a node does not change its contention window after a successful transmission. Only after a node does eight consecutive successful transmissions, its CW is halved. The CW is doubled after a failed transmission (fails receiving the ACK frame). Another sub-class of RA algorithms adopts optimal CW regulation. These include the well known assymptotically-optimal backoff (AOB) [8] and idle sense (IS) [9] algorithms. AOB optimizes the IEEE 802.11 throughput and assumes that the optimal medium access is almost independent of the number of active stations. IS [9] tries to adapt the node's access behaviour that maximizes the throughput by minimizing the time wasted in contention and collisions, and thus increasing the available time for transmissions.

Other MAC protocols, such as [10] consider fixed-length contention schemes. In [10], it is assumed a fixed congestion window with a selective tournaments scheme that begins with a sensing period that only goes to a contention resolution protocol (CRP) after sensing a long period with no emission. The CRP divides the time into time slots that correspond to rounds of selection that are used to leave only a remaining station at the end. Other classes of RA algorithms have been proposed for sensor networks, which are particularly concerned with energy consumption minimization. In this work the proposed mechanism is inspired on the SCP-MAC [1] and CT-MAC [2] protocols for WSNs. SCP combines scheduling with channel polling to minimize energy consumption. The original SCP's two-phase collision avoidance mechanism employs two contention windows separated by a wake-up tone, as illustrated in Fig. 1. In the first CW the nodes that intend to transmit send a wake-up tone to inform other potential sender nodes. The nodes that send the wake-up tone, pass to the second CW and transmit the data packet if the node does not detect a busy channel, as depicted in Fig. 1. CT-MAC [2] considers the contention resolution scheme from [11] jointly with two contention windows similar to the ones in SCP [1]. In CT-MAC two tournaments occur (one per CW) in which multiple time slots are allocated to nodes that compete for the medium in each CW. Only the nodes that won the two tournaments and transmit a busy tone will send its data packet.

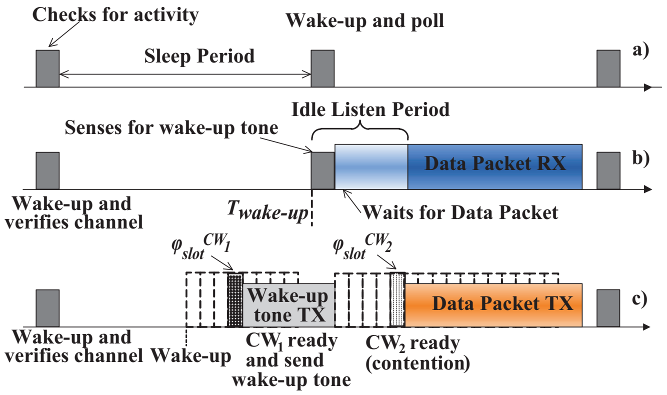

Fig. 1. SCP's two-phase contention window mechanism: a) Sensor node neither has data to be sent nor to be received; b) Sensor node is ready to receive data; c) Sensor node has data to be sent.

III. A TWO-PHASE CONTENTION WINDOW MAC PROTOCOL

A. Protocol Description and Analysis

Most of the distributed MAC protocols proposed for decentralized single-hop networks adopt a single contention phase [3], [5], [12]–[14]. Our proposal, titled TPCW, uses two contention phases, where different contention windows are adopted as illustrated in Fig. 2. The contention window sizes applied in the first and second contention phase are represented by CW$_1$ and CW$_2$, respectively. Nodes randomly choose a slot in each contention window from the interval $[1, CW_1^{max}]$ and $[1, CW_2^{max}]$. In CW$_1$ all nodes that contend have to wait the entire duration of the contention window, whereas, in CW$_2$ the nodes only have to wait until the selected slot, since the data packet is immediately transmitted after the selected slot.

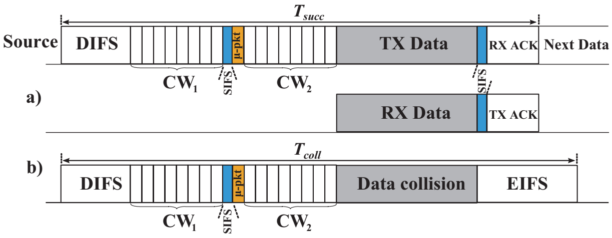

Fig. 2. Two-phase contention window mechanism frame structure: a) successful transmission situation; b) collision situation.

The nodes that contend in the first contention randomly select one slot, informing by this way the other nodes that there are one or more nodes interested in accessing the medium to transmit. The nodes adopt a approach that considers the transmission of a micro-packet (μ-pkt) to announce its intention to send data. A node may transmit a μ-pkt lasting one slot in order to be detected by its neighbours. The node(s) wait(s) a SIFS duration after the end of the first contention window to guarantee a time guard interval. Only the nodes transmitting a μ-pkt in the first non-idle slot of CW$_1$ will successfully pass to the second contention window.

The nodes passing to the second contention phase start the execution of the second window after the SIFS duration, as presented in Fig. 2. The nodes which have data to be sent utilize the TPCW mechanism, while the remaining ones wait for the data packet reception. When more than one node succeeds in CW$_1$, a collision occurs in CW$_2$ if the nodes that have been selected for the second contention phase in CW$_1$ randomly choose the same time slot in CW$_2$. If the first slot chosen by a node in CW$_2$ is selected by a single node, then the data packet transmission is initiated. After the receiver node finishes receiving the data packet, it waits for a SIFS duration, in order to transmit an acknowledgement packet to the node that has sent the data packet. In case of a data packet collision in CW$_2$, a node detecting the collision waits an extended interframe space (EIFS) duration before it attempts to transmit a data packet by repeating all the process above described, as shown in Fig. 2.

B. Analytical Model

First of all, in the following deductions it is considered that all transmitting nodes always have data to transmit (saturated traffic condition). We start defining the collision probability of a node that runs the TPCW mechanism and belongs to a network formed by n_1 nodes. Let P_1 denote the probability of a node choosing a slot in CW$_1$, which is given by

$$P_1 = \frac{1}{CW_1^{max}}. \tag{1}$$

The probability that l nodes choose the same slot, is expressed by the binomial distribution of l nodes choosing the slot with probability P_1, and is denoted as

$$Pr(X = l) = \binom{n_1}{l} P_1^l (1 - P_1)^{(n_1 - l)}, \tag{2}$$

where X represents the number of nodes that choose a specific slot in CW$_1$.

The expected number of contending nodes in CW$_2$, n_2, depends on the probability that the i-th lowest order slot in CW$_1$ is chosen by one or more nodes. At least one node successfully passes from CW$_1$ to CW$_2$ if $n_1 \geq 1$. The expected number of contending nodes in CW$_2$ therefore includes the nodes that had chosen the lowest order slot in CW$_1$ and is given by

$$n_2 = \left\lceil \sum_{k=1}^{n_1} k Pr(X = k) \right\rceil, \tag{3}$$

where the function $\lceil x \rceil$ denotes the ceiling function. The ceiling function is used to avoid $n_2 < 1$ as well as decimal values, since n_2 is an expected integer value greater than 0.

The numerical solution of the collision probability in CW$_2$ depends upon the combination of the different slots' probabilities, namely the probability of finding an idle slot, or the probabilities of finding a busy slot due to a collision or successful transmission. In turn, the probability that a node chooses a given slot in CW$_2$ is the same for all nodes and is given by

$$P_2 = \frac{1}{CW_2^{max}}. \tag{4}$$

Assuming a network composed by n_1 nodes, where n_2 nodes successfully passed from CW$_1$ to CW$_2$, the probability that one node finds the channel idle, is related with all the n_2 nodes that do not start transmitting in the same slot. Consequently, the probability of a slot being idle in CW$_2$ is given by

$$P_{idle} = (1 - P_2)^{n_2}. \tag{5}$$

Accordingly, the average number of expected consecutive idle slots in CW$_2$ observed on the channel is given by the sum of all the idle slots *burst* lengths possible to be obtained. If the network is composed by more than a single node ($n_1 > 1$), the expected number of consecutive idle slots is given by

$$s_{idle} = \sum_{k=1}^{CW_2^{max}-1} k(1 - P_{idle}) \left[P_{idle}^k\right]^{\mathbb{1}_A(n_2)} \tag{6}$$

where $\mathbb{1}_A(n_2)$ is an indicator function given by

$$\mathbb{1}_A(n_2) = \begin{cases} 1, & n_2 > 1 \\ 0, & n_2 = 1 \end{cases} \tag{7}$$

The probability of successfully transmitting in CW$_2$ depends on the number of nodes that choose a slot to transmit. A node successfully transmits if it is the unique node choosing the lowest order slot in CW$_2$, while the remaining $n_2 - 1$ nodes on its radio range do not start a transmission in the same time slot. Thus, the probability of occurring a successful transmission in a given slot of CW$_2$ is defined by

$$P_S = n_2 P_2 (1 - P_2)^{(n_2 - 1)}. \tag{8}$$

In turn, the probability of the remaining $n_2 - 1$ neighbouring nodes do not start a transmission in the same slot is given by

$$P_I = (1 - P_2)^{(n_2 - 1)}. \tag{9}$$

The probability of collision in a given slot of CW$_2$ depends on the number of nodes that choose the same lowest order slot to access the medium. This event corresponds to an effective data packet loss due to a collision. Hence, the probability of occurring a collision in a given slot of CW$_2$ is given by

$$P_C = \sum_{k=2}^{n_2} \binom{n_2}{k} P_2^k (1 - P_2)^{(n_2 - k)}. \tag{10}$$

C. Performance Metrics

Based on the analytical model for the collision probability of the TPCW mechanism, we are able to model the different metrics, such as the aggregate throughput, total transmission delay experienced in all attempts and reliability. Table I presents the values for the parameters considered in the verification of the proposed MAC protocol.

TABLE I
VALIDATION PARAMETERS FROM IEEE 802.11 STANDARD (FOR A TRANSMISSION BIT RATE OF 11 MBIT/S).

t_{DIFS}	50 μs	t_{ACK}	304 μs
t_{SIFS}	10 μs	t_{DATA}	1704 μs
t_{slot}	20 μs	W_1	32
t_{EIFS}	364 μs	BC stages (m_rtx)	7

The throughput depends on the average delay per transmission, T_x, defined as the time a node waits in average to send the packet (and results either in a collision or in a successful transmission). The average delay per transmission is given by

$$T_x = t_{DIFS} + CW_1^{max} t_{slot} + t_{SIFS} + t_{slot} s_{idle} + T_C + T_S, \tag{11}$$

where T_C is defined as

$$T_C = \frac{P_C}{P_C + P_S} T_{coll}, \tag{12}$$

and T_S is given by

$$T_S = \frac{P_I}{P_C + P_S} T_{succ}. \tag{13}$$

The time duration of a packet collision, T_{coll}, is given by

$$T_{coll} = t_{DIFS} + t_{DATA} + t_{EIFS}, \tag{14}$$

while the time duration of a successful packet transmission, T_{succ}, is defined as

$$T_{succ} = t_{DIFS} + t_{DATA} + t_{SIFS} + t_{ACK}. \tag{15}$$

Consequently, the aggregate throughput, S, is obtained by considering the average delay per transmission and is expressed by

$$S = \frac{P_I \cdot t_{DATA}}{T_x} \tag{16}$$

In turn, the reliability, φ, characterizes the probability of a node successfully transmitting a frame within the allowed interval of transmission attempts, and is defined as

$$\varphi = 1 - (1 - P_I)^{m\_rtx}, \tag{17}$$

where m_rtx is the maximum number of retransmissions before dropping a packet [3].

Finally, we define a metric for evaluating the average time duration required to successfully transmit a data packet in the m_rtx attempts. The total transmission delay, D_t, for a node to successfully transmit a packet (or dropping the packet after running out m_rtx attempts) is given by

$$D_t = \sum_{k=1}^{m\_rtx} T_x (1 - P_I)^{(k-1)}. \tag{18}$$

IV. PERFORMANCE EVALUATION

In this paper, we evaluate the reliability, total transmission delay and aggregate throughput, as a function of the contention window sizes (i.e., CW_1^{max} and CW_2^{max}) for the TPCW scheme. Two different contention window sizes are assumed, $CW_k^{max} = 8$, $k \in \{1, 2\}$ and CW_1^{max}=4, CW_2^{max}=64. We do not take into account the hidden terminal, nor the multirate problems. In addition, we study the performance of our TPCW scheme in comparison to the IEEE 802.11 DCF model. The IEEE 802.11 parameters used in the simulation were the ones presented in Table I, with the number of backoff stages given by BC and the minimum and maximum contention windows adopted were 32 and 1024, respectively. Simulation results are obtained in terms of average values from a significant amount of iterations through MATLAB simulations. In order to evaluate the performance and validate the model for the TPCW mechanism, we used the parameters from Table I. It is assumed a single-hop network with no hidden terminals. Saturated traffic is assumed. A fixed number of nodes, n_1, compete to access the wireless medium. Figures 3, 4 and 5 show the dependence of the reliability, normalized total delay and aggregate throughput on the number of nodes, respectively. Our proposed two-phase contention window control scheme is compared with the IEEE 802.11 DCF.

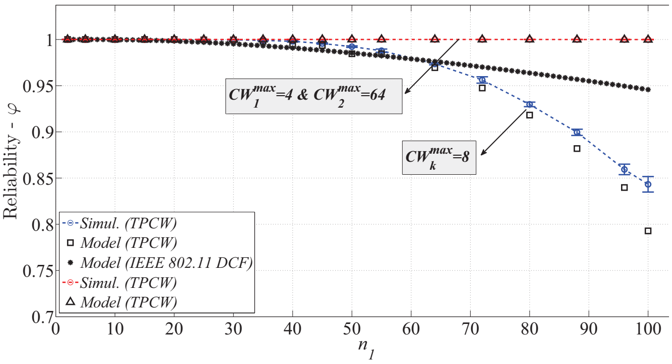

Fig. 3. Comparative results for the reliability and validation of the TPCW and IEEE 802.11 DCF mechanisms, for $k \in \{1, 2\}$.

Figure 3 presents the simulation results along with numerical solutions for the reliability, computed for the TPCW and IEEE 802.11 DCF mechanisms. As depicted in Fig. 3, the reliability is the same and attains the maximum value up to a network size of 20 nodes (a small network) for both schemes. It is observable that for DCF scheme there is then a degradation of the reliability for network sizes larger than 20 nodes. This is due to the increase of the collision rates that result from the increase of the contention in the channel. By comparing the results from the TPCW scheme (for a contention window size of $CW_k^{max} = 8$ slots, $k \in \{1, 2\}$) with the ones from the

DCF scheme, it is observable that the reliability of the TPCW scheme decreases sharply for networks larger than 60 nodes, and has a performance worse than DCF. From this test, we concluded that the sizes of the two contention windows should be increased in order to decrease the collision rates. Hence, for contention window sizes of CW_1^{max}=4, CW_2^{max}=64 slots, the TPCW scheme allows for attaining the maximum value for the reliability as the number of nodes increases. It clearly outperforms the IEEE 802.11 DCF [15] scheme. One solution to increase the reliability of the IEEE 802.11 DCF scheme is to increase the maximum size of the contention window. However, by increasing the maximum size of the contention window, the total transmission delay will also increase, as demonstrated in the work from [15]. We have obtained a maximum improvement of 5% in the reliability for the case of contention window sizes CW_1^{max}=4 and CW_2^{max}=64. For $CW_k^{max} = 8$, $k \in \{1, 2\}$, there is no improvement for larger network sizes.

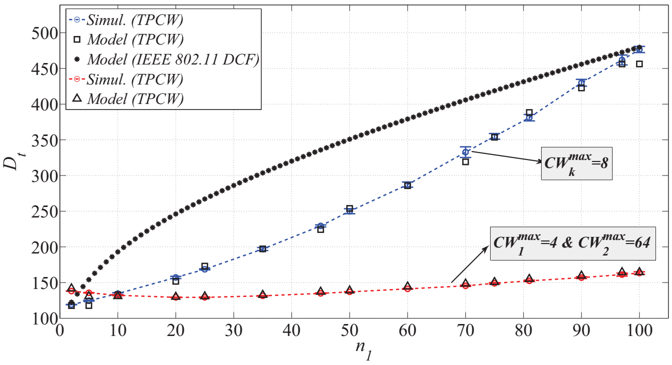

Fig. 4. Normalized results for the total delay (D_t) and validation of the TPCW and IEEE 802.11 DCF mechanisms, for $k \in \{1, 2\}$.

In Fig. 4, IEEE 802.11 DCF achieves a maximum total delay (in slots) of around 480 slots for a network size of 100 nodes. It is observable that, as the number of nodes increases, the total delay increases due to the value of backoff window size, W_i, that is doubled after each retransmission. In the case of contention window sizes, $CW_k^{max} = 8$, $k \in \{1, 2\}$, the total delay behaves in the same way as the one from the IEEE 802.11 DCF (i.e., it increases as the network size becomes larger). However, there is a noticeable difference in terms of total delay between both schemes, as TPCW clearly outperforms DCF. It is also observable in Fig. 4 that, for the TPCW scheme with contention window sizes $CW_k^{max} = 8$, $k \in \{1, 2\}$, the total delay (in slots) achieves a maximum value of around 440 slots for n_1= 100 nodes. By modifying the contention window sizes from the TPCW scheme to CW_1^{max}=4 and CW_2^{max}=64, the decrease of the total delay becomes notorious compared to the DCF model. For this configuration, the TPCW scheme allows the nodes to deliver packets with shorter total delay (even for larger network sizes). Only for networks larger than 50 nodes the delay slightly increases. It reaches a maximum of around 164 slots for n_1= 100 nodes. This shows that the TPCW scheme adds significant improvements in comparison to the IEEE 802.11 DCF scheme. It is worthwhile to mention that a maximum improvement of around 25% is obtained in delay for the case of contention window sizes $CW_k^{max} = 8$, $k \in \{1, 2\}$. In turn, with a contention window configuration of CW_1^{max}=4, CW_2^{max}=64, there is a maximum improvement of around 65% for a network of 100 nodes. As clear from the figure, the delay predicted by the model has the same tendency as the simulated one. For the TPCW scheme, the model slightly underestimates the actual delay mainly due to the simplified assumptions on the collision probabilities that have a impact in the values of the delay. It presents a maximum deviation of approximately 5% from the simulated value. By increasing the contention window sizes (to CW_1^{max}=4 and CW_2^{max}=64) simulation and analytical results become well fitted.

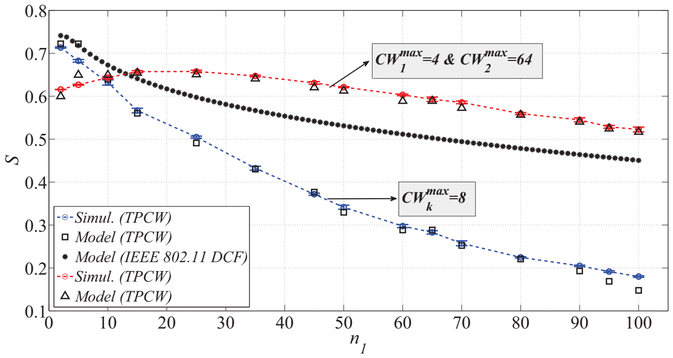

Fig. 5. Results for the normalized aggregate throughput and validation of the TPCW and IEEE 802.11 DCF mechanisms, for $k \in \{1, 2\}$.

As depicted in Fig. 5, for n_1= 10 nodes, the normalized aggregate throughput, computed by dividing t_{DATA} and T_X by t_{slot} in (16), is the same (around 0.65) for the TPCW (for both contention windows sizes configurations). Whereas, for the DCF scheme the normalized aggregate throughput is slightly higher than the TPCW scheme. Figure 5 shows that the IEEE 802.11 DCF scheme achieves a maximum aggregate throughput of 0.74 for a network size of 2 nodes. When the network size value is lower than 15 nodes (small network sizes), the throughput of the TPCW scheme (in both configurations for the contention windows) is lower than for DCF. For network sizes larger than 15 nodes, there are two different behaviours for the aggregate throughput in the TPCW scheme, compared to the DCF scheme. For the TPCW scheme with $CW_k^{max} = 8$, $k \in \{1, 2\}$, the aggregate throughput sharply decreases as the number of nodes increases. This is due to the increase of the collision ratio among nodes. In turn, if we consider contention window sizes, CW_1^{max}=4 and CW_2^{max}=64, the TPCW scheme presents higher values for the aggregate throughput, compared to the DCF scheme.

The maximum gain achieved is around 12% for the case of contention window sizes CW_1^{max}=4 and CW_2^{max}=64. For contention window sizes $CW_k^{max} = 8$, $k \in \{1, 2\}$, there is no improvements for networks larger than 15 nodes. Results from the TPCW model for $CW_k^{max} = 8$, $k \in \{1, 2\}$ present some deviation relatively to the simulation results, although they follow them for larger number of nodes. This is due to the rounding operations that have been applied in the collision probability model proposed in this work, and considered to derive the performance metrics. From Fig. 5, it is observable that the analytical model overestimates the aggregate throughput in some points of the curve until a network size of n_1= 10 nodes for both configurations for the contention windows. For network sizes higher than n_1= 10 nodes, the simulation and analytical results present a good match, as the number of nodes in the network increases. Even though there are some deviations, the solutions given by the model are contained within the simulation error interval, which successfully verifies the validity the proposed collision probability model.

In terms of performance, the TPCW mechanism presents better results than DCF since the BEB algorithm starts with a contention window size of 32 slots and it only achieves the same collision probability of the TPCW mechanism (for CW_1^{max}=4, CW_2^{max}=64) after two retries. This increases the total transmission delay and decreases the reliability of the IEEE 802.11 DCF. After a successful transmission of the packet the node in a IEEE 802.11 DCF network decreases the contention window size again to a size of 32 slots. If the node needs to transmit a packet for the same conditions, it has to wait again for two retries in order to transmit successfully the packet. The way how the size of the contention window is tuned by the BEB algorithm is not optimal.

V. CONCLUSIONS

This paper proposes the TPCW access mechanism that enhances the aggregate throughput and access reliability while decreasing the medium access delay. The new contention mechanism is composed by two different contention stages, which aims at decreasing the number of nodes that effectively compete for the channel, improving the scalability of the protocol when higher scalability networks are considered. The paper characterizes the performance of the TPCW mechanism for different parameterization values and compares it with IEEE 802.11 DCF standard. An analytical model for different performance metrics is proposed for the TPCW mechanism and is validated by means of simulations. The analytical model for the TPCW scheme (for $CW_k^{max} = 8$, $k \in \{1,2\}$), presents a good match with the simulated reliability results, total transmission delay and aggregate throughput, presenting a maximum deviation of approximately 5% from the simulated value. The analytical model for the TPCW scheme (for $CW_k^{max} = 8$, $k \in \{1,2\}$), presents a good match with the simulated reliability results, total transmission delay and aggregate throughput, presenting a maximum deviation of approximately 5% from the simulated value. Considering the TPCW scheme with $CW_k^{max} = 8$, $k \in \{1,2\}$, for network sizes smaller than 10 nodes, simulation and analytical results present some deviations in terms of total transmission delay and aggregate throughput. The deviations are justified by the rounding operations of the expected number of nodes that pass from CW_1 to CW_2, namely when the expected number of nodes is lower than 1. Even though there are deviations, the model is contained in the simulation error interval which successfully verifies the validity of the model.

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