Transmit And Reserve (TAR): a Coordinated Channel Access for IEEE 802.11 Networks

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***Abstract*—This paper considers the medium access problem in the IEEE 802.11 standard. Although the transmission bit rates have clearly increased, some MAC related problems remain unsolved. The random channel contention suffers from short term unfairness and from the considerable reduction of the effective throughput due to the collision probability that increases with the number of contending nodes in the network. Our objective is to define a coordinated access mechanism that improves the effective throughput and grants a fair share of the resources among the network nodes.**

We propose Transmit And Reserve (TAR), a novel packet based coordinated channel access mechanism that combines advantages from random access and channel assignment. The idea of TAR mechanism is simple: Prior to transmitting a packet, the sender node selects in advance the backoff value for its next packet and advertises this selection within the currently transmitted packet. The neighbor nodes avoid then choosing the same backoff value as the advertised one. The simulation results showed that TAR leads to higher throughput and fairness, and lower collision rate than IEEE 802.11. TAR adapts fast to the network load and to the number of active nodes.

I. INTRODUCTION

The last decade has witnessed an unexpected growth of wireless networking triggered by the success of the IEEE 802.11 standard [1]. This growth reflects the still increasing interest of the academia and the industry to improve its performance. Successive variants of the standard focused on increasing the bit rate (multi bit rate, the a, g, and n variants). Nevertheless, the MAC layer remains practically unchanged despite the efforts to improve it. The random access scheme of IEEE 802.11 suffers from the inefficient exploitation of the bandwidth [2], [3] and from short term unfairness [12]. The collision rate experienced in the IEEE 802.11 random access scheme increases with the number of contending nodes. The collisions reduce the bandwidth efficiency of the access scheme and perturb the operation of higher layer applications as well. Following a collision, the IEEE 802.11 applies the exponential backoff algorithm in order to reduce the access probability of colliding nodes leading to short term unfairness. The colliding nodes are more probable to choose higher backoff values which delays further their transmission attempts. Although many improvements to the IEEE 802.11 access scheme have been proposed, most of them still rely solely on the random access mechanism and therefore still suffer from the limitations of the IEEE 802.11. Improving the channel access scheme in IEEE 802.11 standard is equivalent to minimizing the effect of collisions while at the same time providing a fair distribution of the resources among the network nodes. In particular, it can be enhanced by coordinating the channel access between the different contending nodes to reduce the collisions occurrences. In the case of IEEE 802.11, this is possible if we succeed in defining a mechanism that organizes the channel access in a such a way where each node selects a different backoff value from those maintained by the rest of the nodes.

In this paper, we present Transmit And Reserve (TAR) that is a packet based coordinated channel access scheme for IEEE 802.11 networks. TAR tries to organize the network access into a cycle where each source node has one channel access trial per cycle. By organizing the network in a cycle, TAR improves the bandwidth exploitation and the short term fairness of the access scheme. The TAR cycle is the result of a distributed coordination between the different sources in the network. This distributed coordination is accomplished by the advertisement of the selected backoff value by each node. Prior to transmit a packet, the sender node selects in advance the backoff value for its next packet waiting for transmission. This selected backoff advertisement allows the rest of the nodes to avoid already selected values. We show using extensive simulations that TAR improves significantly the throughput and the short term fairness compared to IEEE 802.11 standard.

The rest of the paper is organized as follows: In section II we introduce TAR access mechanism, we describe its operation and present its main properties. In section III we provide the simulation evaluation of TAR and show how it outperforms the IEEE 802.11 standard. In section IV we present some related work before we conclude in section V.

II. TRANSMIT AND RESERVE (TAR)

Transmit And Reserve (TAR) is a per-packet coordinated channel access scheme for IEEE 802.11 wireless networks. The objective of TAR is to define an access method that optimizes the throughput, reduces the number of collisions and provides high short term fairness. The idea of TAR is to create a cycle of active nodes[1] accessing sequentially to the channel.

A. TAR Channel Access

The IEEE 802.11 MAC is based on the CSMA/CA random access where a node backoffs a randomly selected number of slots before attempting to transmit. Using this algorithm, two or more nodes may have the same backoff value at a given moment and a packet collision may therefore occur. The key idea of TAR is to support the network nodes with the means to avoid selecting backoff values that are already selected by other nodes. By avoiding the already selected backoff values, the major reason for collisions will be eliminated. To achieve this objective, TAR defines a mechanism that consists of:

- Selecting in advance a *free backoff* [2] value for the next packet waiting for transmission,
- Advertising (reserving) the selected backoff value within the current packet to transmit,
- Maintaining a *Backoff Reservation* counter in order to track the advertised (reserved) backoff values in the network.

Using this mechanism, TAR tries to organize the network into a cycle where each active node accesses once to the channel. The TAR cycle is the result of the advertisement of selected backoff values and the synchronization of the maintained *Backoff Reservation* counters to the most up-to-date advertisement. By making all the nodes synchronize their *Backoff Reservation* counters to the same received advertisement, TAR creates a kind of a common counter maintained separately by each node. Prior to transmit a packet, the source node updates its *Backoff Reservation* counter value by adding to it a predefined *step* parameter value with *step* ≥ 2. Then, it sets the backoff value for the next packet waiting for transmission to the updated *Backoff Reservation* counter and advertises this *selected backoff* in the current packet to transmit. Upon reception of this advertisement, the receiver nodes update their *Backoff Reservation* counters to fall back again on a common value within the network. When a node senses an idle slot on the channel, it decrements by one the values of its backoff and *Backoff Reservation* counters.

As the *step* parameter value is ≥ 2, some free slots will exist between two consecutive TAR selected backoffs. This allows new nodes to join the TAR cycle by randomly choosing a backoff value from the gaps of free slots between the reserved selected backoff values. As described above, the operation of TAR consists in selecting in advance and advertising (reserving) the *selected backoff* value for the next packet waiting for transmission. However, a node may not always have data to transmit. Therefore, the TAR access scheme is divided into: (1) random access phase where a node joins the coordinated transmission cycle and, (2) Coordinated access phase where a node participates in the TAR access cycle as long as it has more packets waiting for transmission.

1) TAR Random Access Phase: This phase of TAR access scheme differs depending on whether there exists already an access cycle in the network (joining a cycle) or not (creating a cycle). A node can detect the existence of a TAR cycle by checking the value of its *Backoff Reservation* counter.

- **Creating a cycle:** This is the case when the value of the maintained *Backoff Reservation* counter is equal to zero, this means that there exists no reservation in the network. In this case, the node operates as the IEEE 802.11 DCF mode. This means it randomly selects a backoff value in the range of $[0, CW_{min}[$. When this backoff timer expires, and the node has more data to send, it sets its backoff and *Backoff Reservation* counters to CW_{min} to avoid selecting an already chosen backoff value. Then, it advertises the *selected backoff* in the packet to transmit. This way the node creates a cycle that comports only one node for the moment, which is the sender itself. If the node has no more data waiting to be sent it simply advertises the value of 0 in the packet to transmit.
- **Joining a cycle:** This is the case when the value of the maintained *Backoff Reservation* counter is not null. The node here has to choose a random backoff value from the free idle slots between the different reserved values. The reserved values are detected based on the *Backoff Reservation* counter and the *step* parameter values. For example, if the current *Backoff Reservation* is 13 and the $step$ parameter value is 3, then the backoff values 13, 10, 7, 4 and 1 are reserved (arithmetic progression starting from the *Backoff Reservation* counter value and subtracted by multiples of the *step* parameter value). When the backoff timer expires and the node has more data to send, it applies the mechanism described in the coordinated backoff reservation phase below.

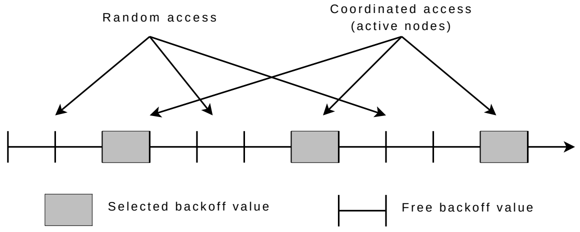

Figure 1. Separation between TAR's random and coordinated access phases.

2) Coordinated Access Phase: This phase involves the nodes already participating within the access cycle. A node, that we are calling active node, belonging to the access cycle has more data waiting for transmission at the moment of sending a packet. When the backoff timer of an active node expires, it adjusts its own *Backoff Reservation* counter value BOR to $BOR + step$ and sets the backoff timer for the next transmission to the same value $BO = BOR$. Then, it advertises this *selected backoff* value within the packet to transmit. This operation allows a node to select in advance

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[1] By active node we mean a greedy source that has always data waiting to be sent on the wireless interface.

[2] A free backoff is a value that is not already selected by any other node at the moment of selection.

the backoff value for its next transmission and to continue participating in the access cycle as long as it has more data to send. If the node has no more data waiting for transmission, it simply inserts the current value of its *Backoff Reservation* (without modification) in the packet to transmit to leave the TAR cycle.

Figure 1 illustrates the TAR's organization of the channel access in coordinated reserved access and random access.

B. Applicability of TAR

TAR channel access scheme is designed for wireless networks. Its basic component consists of selecting in advance and advertising the *selected backoff* values of the nodes accessing to the channel. In order to work properly, all the nodes should synchronize to the *selected backoff* advertisement. In other words, TAR can be applied in

- A fully meshed environment where all the nodes are neighbors.
- An access point environment where all the nodes are neighbors of the access point. In such network, the RTS/CTS handshake needs to be used to overcome the hidden node problem. The synchronization to the *selected backoff* advertisement will be done upon reception of either the RTS or the CTS messages.

C. TAR Protocol Specification

TAR requires each node to maintain two counters: the backoff counter as specified by the IEEE 802.11 standard and a *Backoff Reservation* counter. The *Backoff Reservation* counter is synchronized to the *selected backoff* advertised in received messages and it is decremented by one when the node senses an idle slot.

- **Idle slot sensing:** When a node senses an idle slot, it decrements by one the values of the backoff and the *Backoff Reservation* counters if they are set (value > 0).
- **Reception of a message:** When a node receives a message, it compares the value of the advertised *selected backoff* value ($Adv(v)$) in the message to its own *Backoff Reservation* (BOR) counter value. If $Adv(v) > BOR$ then the node updates its *Backoff Reservation* to $BOR := Adv(v)$. If the node is the destination of the received message, it advertises in the ACK reply the updated *Backoff Reservation* counter value.
- **Transmission of a message:** When a node has a message to transmit and its backoff timer is not set, it checks the value of the *Backoff Reservation* counter. If $BOR = 0$, (no cycle in the network) the node selects a random backoff value in the range $[0, CW_{min}]$. If $BOR > 0$ then the node selects a random backoff value from the free idle slots. If the backoff timer is set, the node simply waits for it to timeout.
- **Backoff timeout:** When the backoff timer of a node times out and the node has more data to send, (can be detected by checking the interface queue length) two cases can be identified: If $BOR = 0$, this means the node is the first to initiate the access cycle, then the node sets its *Backoff Reservation* counter value to $BOR = CW_{min}$. If $BOR > 0$ then the node updates its *Backoff Reservation* counter value to $BOR = BOR + step$ and sets the backoff of for the next packet to transmit to $BO = BOR$. The *Backoff Reservation* requires no update if the node has no more data to transmit. Then the node advertises the value of the *selected backoff* within the message to transmit (DATA or RTS).
- **Reception of a CTS message:** When the sender receives a CTS message, it compares the *backoff reservation* value to its *Backoff Reservation* counter value. If $Adv(v) > BOR$ (this means the sender does not have an updated BOR value), then it updates its *Backoff Reservation* to (1) $BOR = Adv(v) + step$ if it has more data to send and sets its backoff counter to $BO = BOR$, or to (2) $BOR = Adv(v)$ if it has no more data to send. In both cases, the node advertises the value of the *Backoff Reservation* within the message to transmit.
- **Reception of an ACK:** When the sender receives an ACK to its transmitted message, it compares the advertised *selected backoff* value to its *Backoff Reservation* counter value. If $Adv(v)! = BOR$, then the node has a confusion in its *Backoff Reservation* counter. This case should not happen normally since the sender should have an updated BOR value. However in this case, the node sets its *Backoff Reservation* counter to $BOR = 0$ and applies the random backoff access if it has more data to send.

D. Properties of TAR

TAR organizes the channel in a cycle of active nodes accessing sequentially to the channel. This property guarantees a high throughput and short term fairness among the different nodes. In addition, TAR performs the channel coordination in a completely distributed manner through the advertisement of the *selectd backoff* reservation. TAR is suitable for dynamic networks as it supports using simple procedures the arrival and departures of nodes.

1) Short Term Fairness: We consider here the fairness in the channel access, which is the number of transmission tries granted to different nodes according to the access scheme. TAR organizes the channel access into a cycle of active nodes where each node transmits once in a cycle. Assume there are N active nodes in the network, the TAR cycle will be composed of N consecutive transmission tries providing thus a very high short term fairness.

2) High Throughput and Low Collision: The throughput of an access scheme depends on the portion of the channel spent in successful transmissions and on the transmission bit rate. If we consider for instance that the bit rate and the packet size are the same for all nodes, improving the successful transmission share of time implies the improvement of the throughput. Theoretically, using TAR access scheme, collisions between the nodes participating within the cycle can be avoided. This is due to the fact that within a cycle, each node selects relatively the same backoff value in a different moment in time.

Therefore, if we assume that all the nodes of the network are participating in the cycle (total saturation case), the collisions can be effectively avoided.

3) Fast Convergence and Adaptation to the Network Load: In a wireless environment, a node may join or leave the network at any moment. Moreover, it may alternate between active and idle states. For these reasons, TAR should support in a simple and efficient way the joins and departures of nodes. Using TAR, a new active node goes first through the random access phase before advertising its *selected backoff* for its next transmission and joining thus the access cycle. To leave the cycle, the node simply makes no backoff reservation. These simple join and leave procedures make TAR adaptable to the network load.

III. TAR EVALUATION

In order to evaluate our mechanism, we implemented TAR with all its features as a MAC layer in NS-2. We studied the performance of TAR in a fully meshed network and compared it to IEEE 802.11 DCF mode. The number of nodes was varied from 2 to 100 nodes. For every density 25 different random simulations have been carried out and the results averaged. We performed most of the measurements using User Datagram Protocol (UDP) traffic to study the behavior of TAR in a saturation condition. UDP traffic is sent at Constant Bit Rate (CBR), and packet size at MAC layer of 1500 bytes, with a sending rate sufficient to have the buffer at Link Layer never empty. The RTS/CTS handshake of the MAC layer in this set of simulations was disabled. In the following sections, we present the main simulation results.

A. Impact of the $step$ Parameter Value

The value of the $step$ parameter has an impact on the performance of TAR access mechanism. Intuitively, a small $step$ parameter value will limit the number of free slots between two TAR coordinated transmissions. However, in a wireless environment, the different nodes will have different channel conditions and may thus sense idle slots at different moments. Therefore the *Backoff Reservation* counter update may not be synchronized. This is a potential source of collisions in TAR access cycle when the $step$ parameter value is relatively small. Accordingly, the value that limits the portion of wasted channel time in both idle slots and collisions should be found. Figure 2 illustrates the throughput gain of TAR with respect to IEEE 802.11 for different $step$ parameter values in 4 network densities. For a small number of active nodes, the difference is marginal for the different values of the $step$ parameter. However, when the number of nodes increases (25 and 50), TAR performs better with the $step$ parameter values of 5 and 6 with an advantage for the value of 5. For this reason, we will use TAR with the $step$ parameter set to 5 in the rest of the simulations.

B. Throughput and Collision Overhead

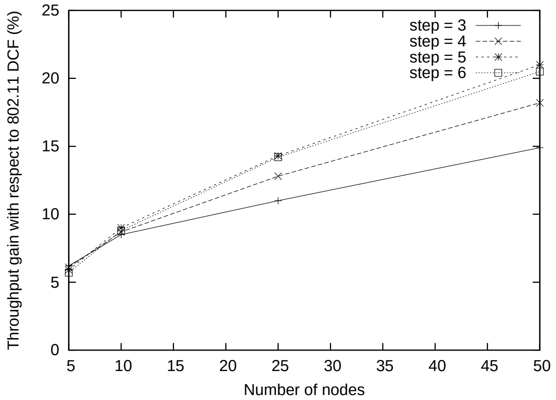

Figure 2. Impact of the $step$ parameter value on the performance of TAR for different network densities.

One of TAR's main objectives is to improve the throughput and reduce the collisions in the network. This is possible thanks to the TAR coordinated access that reduces the MAC channel access cost compared to IEEE 802.11 DCF mode. Figure 3 compares the global throughput of TAR and IEEE 802.11 for a different number of nodes. For a small number of nodes (less than ten), the throughput gain is equivalent to 4.2% for two nodes and reaches 9% for ten nodes. This result was expected as for a small number of nodes the IEEE 802.11 collision rate is still small. However, the throughput gain is significant when the number of nodes is high. It is around 11% for a network of 15 nodes, it increases to 21% for 50 nodes and reaches as high as 39% for 100 nodes. This result was also expected as the bandwidth waste increases with the number of competing nodes in IEEE 802.11. This is not the case with TAR where the coordinated channel access succeeds in preserving the channel efficiency improving thus the throughput. This result can also be deduced from Figure 4 that compares the collision rates of TAR and IEEE 802.11. We can see that the collision rate with TAR is negligible for a small number of nodes and considerably lower than that of IEEE 802.11 for dense networks. This significant difference is due to the random access scheme of IEEE 802.11 where collisions increase with the number of nodes whereas TAR's coordinated channel access succeeds in reducing the collision rate which means less bandwidth waste.

C. Fairness and Access Delay

Short term fairness is an important evaluation criterion of a channel access mechanism as it provides the distribution of the channel time between the different contending nodes on a short timescale. Figure 5 shows the Jain fairness [9] index of TAR and IEEE 802.11 in function of the normalized window size number[3] for two network densities of 5 and 25 nodes. TAR succeeds in providing close to optimal short term fairness. This is due to the coordinated channel access cycle of TAR. When the number of nodes increases, the short term fairness index decreases slightly but remains close enough to the optimal. Contrarily to TAR, IEEE 802.11 suffers from

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[3] For a network of N nodes, a normalized window size of 1 is equivalent to N transmissions.

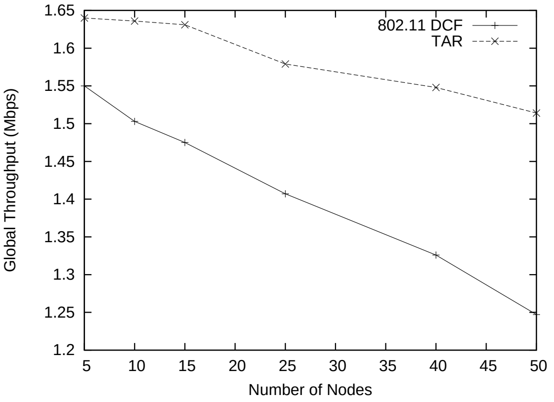

Figure 3. Global throughput comparison between IEEE 802.11 and TAR.

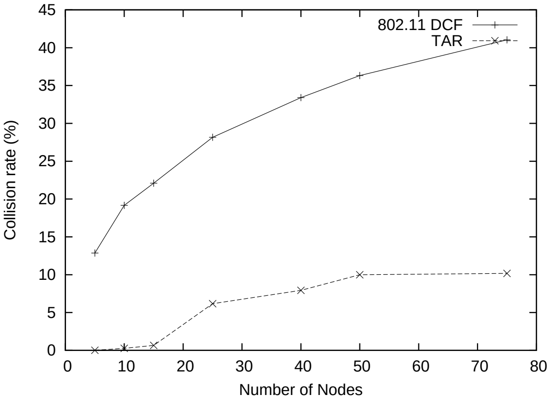

Figure 4. Collision rates for IEEE 802.11 DCF mode and TAR.

short term unfairness that increases considerably with the number of nodes. This result can also be deduced from Table I that presents the average and the standard deviation values of the inter-transmissions delay (the time difference observed between two consecutive transmissions of a given node) of TAR and IEEE 802.11 for different network densities. The average inter-transmissions delay is lower with TAR and the difference increases with the number of nodes. When it comes to the standard deviation, we can see that this value is extremely lower with TAR than with IEEE 802.11 for the different number of nodes. This is due to the coordination in the channel access that makes TAR more appropriate for time constrained applications like voice over IP.

Nb nodes	802.11		TAR	
	avg.	stdv.	avg.	stdv.
5	14.716	17.737	13.707	0.415
10	31.718	61.691	27.470	1.972
25	95.640	241.732	71.087	12.616
50	239.462	579.847	147.407	33.468

Table I
AVERAGE AND STANDARD DEVIATION VALUES IN MILLISECONDS OF THE INTER-TRANSMISSION DELAY OBSERVED OVER $2 \cdot 10^5$ TRANSMISSIONS FOR DIFFERENT NUMBER OF NODES.

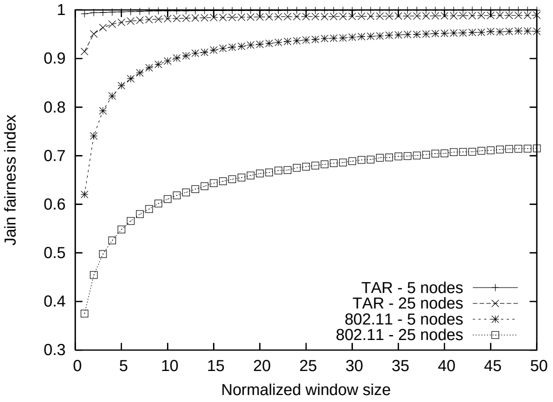

Figure 5. Short term fairness comparison between TAR and IEEE 802.11.

D. Convergence

The value of the advertised *selected backoff* reflects the number of nodes participating in the TAR access cycle and should adapt to the network load. In order to evaluate the convergence speed of TAR, we considered the following scenario. At the start of the simulation runtime, 16 nodes where active. After $40sec$, 5 more nodes joined the network and left it $30sec$ later. At the end of the simulation, we compared the advertised *selected backoff* values of these two sets of nodes. We are particularly interested in moments 40 and 70 of the simulation runtime. The closer the values of the advertised *selected backoff* are the better the convergence of TAR is. Figure 6 shows the convergence speed of TAR. We can see that TAR adapts quickly to the changes in the traffic conditions. Only few transmissions are required to reach the new stable state. Upon nodes arrival and departure, the value of the *selected backoff* was quickly adjusted to adapt to the change in the number of active nodes participating in the access cycle.

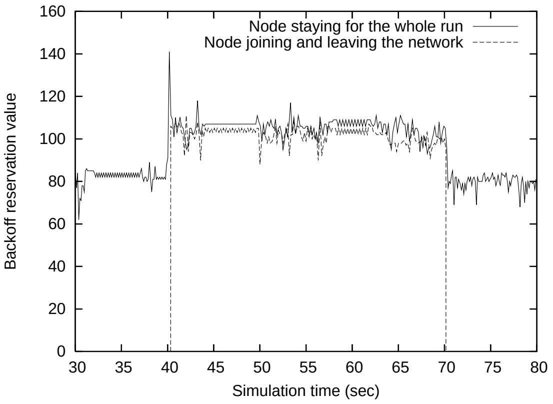

Figure 6. Fast convergence of the TAR access scheme.

IV. RELATED WORK

Despite the wide deployment of IEEE 802.11, its random access scheme suffers from the inefficient bandwidth exploitation and from short term unfairness. There are a number of research proposals on more efficient MAC layers. The use of carrier sensing in IEEE 802.11 MAC to avoid collisions is not perfect in dense networks. The objective then is to have a more efficient local coordination mechanism to reduce the likelihood of collisions. IEEE 802.11 DCF MAC tries to handle collisions by using a temporal approach. Collisions are resolved adaptively by changing the length of the contention window of nodes experiencing collisions. An alternative approach called spatial backoff [13], [16] tries to control the interference region of a node. This can be done using several physical layer capabilities such as transmission power control, rate control or adjusting the physical carrier sensing threshold. Although these methods can improve the performance of the IEEE 802.11 MAC, they still suffer from the random access scheme that is the source of the IEEE 802.11 limitations. The idea in Idle Sense [7], [8] is to make the contention window equal to all the nodes. Each node estimates the number of consecutive idle slots between two transmission attempts and uses it to compute its contention window. By adjusting the contention window, a node makes the mean number of consecutive idle slots converge to a common value (target value) for all nodes optimizing thus the throughput. The SELECT protocol [4] proposes a self-learning collision avoidance strategy to address the hidden/exposed receiver problem in IEEE 802.11 networks. It is based on the observation that carrier sense with received signal strength measurements at the sender and the receiver can be strongly correlated. The sender exploits such correlation using adaptive algorithms and maintains a record of the channel availability at the intended receiver. These proposals are interesting in random channel access as they can further reduce the collision probability. We argue that the MAC can perform better if the channel access is coordinated between the different nodes in order to eliminate the randomness in the channel access.

Other protocols try to eliminate the contention nature of the IEEE 802.11 channel access by proposing a TDMA contention free approach [5], [6], [10], [11], [17]. These proposals succeed in eliminating the random access of IEEE 802.11 and therefore are able to improve the performance of the MAC layer. However, they require major changes to the radio interface of IEEE 802.11 standard. We are interested in providing an access scheme that provides features comparable to TDMA access in terms of efficiency and fairness, while at the same time conserving high compatibility with IEEE 802.11.

The idea in Opportunistic Auto Rate (OAR) [14] is completely different. While it uses the IEEE 802.11 random access scheme, it tries to exploit the durations of high quality channel conditions. OAR opportunistically sends multiple back-to-back data packets whenever the channel quality is good. The work in [15] uses a different approach to achieve the same objective as OAR which is time fairness. It tries to enhance the throughput by varying the fragment size depending on the data rate in order to have same transmission duration. TAR access scheme is complementary with these approaches, they can be combined to improve the channel access scheme while at the same time exploiting good link quality.

V. CONCLUSION

In this paper we proposed TAR, a coordinated channel access mechanism that organizes the channel in a cycle of active nodes. The key idea of TAR is simple; instead of randomly choosing its next backoff value, TAR allows a node to select and advertise a non selected value. By advertising the backoff selection, the network nodes avoid selecting already selected backoff values reducing thus the collision probability. By means of channel access coordination, we showed using NS2 simulations that TAR improves the throughput and short term fairness of IEEE 802.11.

We are currently working on evaluating TAR using other traffic scenarios like TCP and time constrained applications. Our future work consists in generalizing TAR for mobile multihop networks and in investigating its coexistence with IEEE 802.11.

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