Random Access with Repeated Contentions for Emerging Wireless Technologies

Andrea Baiocchi(1), Ilenia Tinnirello(2), Domenico Garlisi(2), Alice Lo Valvo(2)
(1) University of Roma Sapienza, Roma, Italy - Email: andrea.baiocchi@uniroma1.it
(2) CNIT / University of Palermo, Italy - Email: name.lastname@unipa.it

***Abstract*—In this paper we propose ReCo, a robust contention scheme for emerging wireless technologies, whose efficiency is not sensitive to the number of contending stations and to the settings of the contention parameters (such as the contention windows and retry limits). The idea is iterating a basic contention mechanism, devised to select a sub-set of stations among the contending ones, in consecutive elimination rounds, before performing a transmission attempt. Elimination rounds can be performed in the time or frequency domain, with different overheads, according to the physical capabilities of the nodes. Closed analytical formulas are given to dimension the number of contention rounds in order to achieve an arbitrary low collision probability. Simulation results and a real implementation for the time-domain solution demonstrate the effectiveness and robustness of this approach in comparison to IEEE 802.11 DCF.**

I. Introduction

In the last years, the original IEEE 802.11 standard has been extensively amended for providing breakthrough capacity improvements by exploiting the latest PHY enhancements [1][2], such as bandwidth aggregation, efficient modulation and coding schemes, and advanced MIMO (e.g. up to 8 spatial streams in the IEEE 802.11ac). Still the MAC contention procedure is based on random countdown of back-off time slots. Its efficiency has been improved by allowing a station to transmit multiple data frames in a single channel access, but the contention mechanism wastes a significant amount of capacity and introduces jitter of service times due to collisions, and to exponential backoff.

Although not included in current standards, another promising pathway to boost wireless network capacity is full-duplex radio, which is becoming a viable technical solution [3], [4]. As a matter of example, a cancellation capability of up to 110 dB has been demonstrated over up to 80 MHz bandwidth [5]. Full-duplex capabilities have a strong impact on the design of more efficient MAC schemes [6]. However, most of the protocols proposed so far exploit these capabilities for performing collision detection in classical CSMA schemes, thus reducing the collision times [7]. Alternative solutions for improving efficiency are explored in [8], [9], where the concept of contention in the frequency domain is introduced.

Regardless of the specific physical solutions, there are two main issues to be solved for random distributed systems [10]: arbitrating the access to a common channel, and scheduling frame transmissions within the channel holding times. While specific mechanisms have been standardized for introducing flexibility in the management of the channel holding time, such as the set-up of reverse links, cumulative acknowledgments and frame aggregations, in current standards the contention rules cannot be negotiated among the stations. Protocol flexibility is limited to the tuning of some parameters, which specify the contention windows, the retry limits, or the selection of pre-defined operation modes, because the contention logic needs to be implemented in the card hardware and firmware for efficiency reasons, and it cannot be easily extended or updated. An interesting approach for overcoming the technological problem of modifying time-critical MAC operations has been proposed in [11], by envisioning a novel architecture for wireless cards called Wireless MAC Processor (WMP). The card does not implement a specific protocol, but rather a generic *MAC Engine*, able to load and run different MAC programs (from CSMA to TDMA) working on the same hardware functionalities and signals.

In this work, we focus on the possibility to define innovative and flexible contention mechanisms for distributed systems, by leveraging the physical layer capabilities of recent wireless technologies, as well as emerging architectures which support the implementation of programmable MAC protocols. We follow two approaches: a short term one, where the emphasis is on exploiting current off-the-shelf technology; and a longer term perspective, based on recent advances in full-duplex radios. Specific novel contributions of this paper are: (i) the generalization of the contention defined in [9] to any number of contention rounds and to both time and frequency domains; (ii) the development of an analytical model of this new procedure (Repeated Contention, ReCo), yielding an asymptotically tight upper bound of the collision probability and a simple tool for dimensioning the key parameters of ReCo; (iii) experimental results on off-the-shelf WiFi cards, where the new ReCo scheme has been implemented.

In the rest of this paper, after a literature review provided in § II, we define the proposed access procedure in § III, provide an analytical model in § IV, and discuss some dimensioning criteria in § V. An experimental validation is presented in § VI. Finally, conclusive remarks are given in § VII.

II. Related Work

CSMA schemes implemented in current technologies, such as the 802.11 DCF, expose a limited form of flexibility by

This work has been partially supported by EU funded research projects WiSHFUL, H2020 grant agreement 645274, and Flex5Gware, H2020 grant agreement 671563.

enabling the dynamic configuration of contention windows and retry limits, as well as the possibility to activate or not 4-way handshake mechanisms. Several research work have been focused on the optimization of these parameters as a function of the network load and topology. For example, in [12], inspired by the throughput-optimal CSMA theory (e.g., see [10][13]), the Authors present the so called Optimal DCF, that implements in off-the-shelf 802.11 devices the principles of adaptation of contention windows and channel holding times by monitoring the difference between the bandwidth demand and supply of the node. Dynamic tunings of the contention windows for achieving throughput optimality are also performed in *Idle sense*, a DCF variant proposed by Heusse et al. [14]. Starting from the observation that in optimal conditions the number of idle back-off slots between two transmission attempts weakly depends on the number of contending stations, the contention window is dynamically adjusted for making such a number equal to a target limit value. The scheme achieves higher throughput than DCF, although the time to get a reliable estimate of the number of idle slots grows proportionally to the number of stations. Moreover, a fairness issue arises when relaxing the hypothesis that all contending stations share the same current estimate of the contention window [15].

Generalizations of the traditional "linear" DCF contention (i.e., based on a single random extraction over a set of possible back slots) have been proposed in different directions, by considering repeated contention rounds [16], [17] or contentions in the frequency domain [18], [9]. In [16] contending stations decide randomly to transmit a busy signal or not in a contention round of fixed size. Stations that refrain from transmitting the busy signal, listen to the channel and drop out if they sense it busy. The probability to transmit the busy signal in each round and the number of rounds can be optimized in case the number of competing stations are known. Other repeated round contention schemes are provided in [17] and in [19] for handling flows with different priority levels. The analysis is quite involved and does not yield a good insight into the effectiveness of the repeated round concept as a general means for sharing a channel. Contention mechanisms in the frequency domain are explored in [18], [9] where, respectively, one or two consecutive contentions are carried out by selecting random sub-carriers rather than random back-off delays. The stations transmitting on the smallest frequency sub-carrier win the contention round. In [8] frequency domain contention is considered as means to elect a femtocell that transmits on a given channel, for mitigating the interference among nearby femtocells by means of channel reservations. The difference with the present work is that the contention process has a random duration and no collision can occur, i.e., the contention is carried on until exactly one femtocell wins.

Another direction for improving the MAC efficiency is the reduction of control messages' overheads. In [20], control messages like RTS, CTS and ACK are encoded by using Correlatable Symbol Sequences (CSS). The properties of the CSS allow a substantial reduction of the vulnerability intervals and of the air time wasted for transmitting RTS/CTS and ACK frames. In [21] a PHY-based explicit signaling among the AP and the stations and frequency domain contention are proposed. Our scheme relies on additional control signals for solving the contention, but it achieves a significant reduction of the channel overheads due to collisions.

III. Repeated contention procedure

In this section we present a *robust contention scheme* whose performance is not critically affected by the configuration of the contention parameters. The idea is running repeated contention rounds, devised to select a sub-set of stations among the contending ones. The iteration of the basic contention round turns out to be a very powerful mechanism to reduce the collision probability to any desired low level. As discussed in § II, repeated contention round is not a new idea in itself. However, an innovation element of our proposal is decoupling the protocol logic from the physical implementation of the mechanisms used for performing the elimination rounds, and defining a complete, general analytical model.

As long as there are backlogged stations contending for the access to the channel, the channel time is divided into cycles, made up of a *contention phase* and an *activity phase*. During the contention phase, the time axis is divided into s consecutive *contention rounds*. The contention phase is devised to identify the station that is allowed to transmit on the channel in the ensuing activity phase. The activity phase includes all the frame transmissions performed within the same transmission opportunity, i.e., data and acknowledgment frames, or multiple data frames with a final acknowledgment request/response. Whatever the outcome of the activity phase, namely either a successful transmission or a failure, all backlogged stations, take part in the next contention phase, by repeating exactly the same algorithm as performed in the previous cycles. No binary exponential back-off or state variable is required, so that the entire access procedure is regenerated at each new cycle.

Within each contention round, a backlogged station has to choose one 'level' among $m \geq 2$ possible choices. Regardless of the specific mechanism to implement the scheme, the key aspects for supporting repeated contention rounds are:

1) the m levels are strictly ordered; we can label them as the integers of the set $\{1, \ldots, m\}$;
2) during the contention round every contending station can sense whether a level lower than its own choice has been chosen by any other station.

The stations selecting the lowest level win the contention round and move forward to the next contention round. Note that possibly more than one station could win a contention round. For sure, there is *at least* one winner, since this corresponds to the existence of the minimum of a finite set. All the losing stations, having sensed that a level strictly lower than their choice has been selected, drop out of the current contention phase and wait for the next cycle.

In the following we specialize this general concept to specific implementations, in the frequency and time domains. The first one is definitely the way to choose to boost performance,

Algorithm 1 Pseudo-code of the contention phase algorithm.

```
round = 0;
dropout = FALSE
F(i) = sum_{j=1}^{i} q_j    i = 1, ..., m;
while (round < s)&(dropout == FALSE) do
    round = round + 1;
    r = min{x | 1 ≤ x ≤ m , F(x) ≥ rand};
    transmit(round, f_r);
    if r > 1 then
        dropout = isbusy_channel(round, [f_1, ..., f_{r-1}]);
    end if
end while
```

but it requires that each station has the ability to detect other stations' signals *while* they it is transmitting its own signal. We include also the time domain approach, since it can be implemented on commercial off-the-shelf WiFi cards.

A. Frequency domain repeated contention

Repeated contentions can be implemented very efficiently in the frequency domain. A set of m frequencies is defined, denoted with $\{f_1, \dots, f_m\}$. As a matter of example, if the PHY layer is based on OFDM, the m levels to be used for contention can be identified with (a subset of) the available sub-carriers. Let q_i, $i = 1, \dots, m$ the probability that frequency f_i is selected at a given round. The pseudo-code of the contention round algorithm for a station is listed in Alg. 1. In the algorithm, we call the following functions:

- rand: generates a sample uniformly distributed in the range $[0, 1]$.
- transmit(r, f) transmits a busy tone on frequency f during contention round r.
- isbusy_channel$(r, [a, b])$ checks if signal is detected in the band $[a, b]$ during contention round r.

The algorithm states simply that a contending station picks a frequency f_r at random, according to the probability distribution $\{q_i\}_{i=1,\dots,m}$, transmits that frequency and *at the same time* listens to check whether a frequency *lower* that f_r is being transmitted: here it comes into play the full-duplex capability. Note that the contention phase does not require the capability of decoding any message. A station must simply check whether it receives a tone whose frequency is lower than its own choice. This is a special case of full-duplex radio capability demonstrated in [5][4][9].

The station elects itself as winning the contention round if it does not sense any frequency lower than its own choice f_r. In that case the station will move to the next round and it will repeat the contention algorithm just as outlined in Alg. 1. Note that *at least one* station must survive at the end of any contention round, if channel sensing works. If the station goes on winning until the s-th round inclusive, then it has won the contention phase and it has gained a right to use the channel.

The bottom diagram in Fig. 1 shows an example of ReCo in the frequency domain (called ReCo_f), with $s = 2$ and $m = 4$, under the assumption that each contention round lasts exactly one back-off slot. This is a reasonable assumption because it is possible to transmit more than one OFDM symbol within a back-off slot. The boxes along the frequency dimension represent the tones used for the contention round.

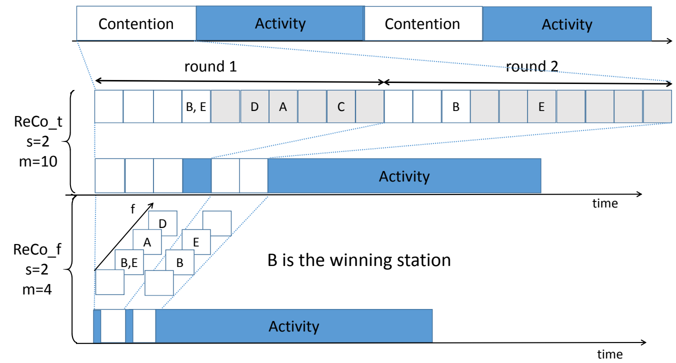


Fig. 1. Channel access operations as a sequence of contention and activity phases: comparison between ReCo in the time (top) and frequency domain (bottom).

Four stations are contending, each marked by a letter. After the first contention round, two stations survive and are admitted to the second round, after which only station B survives. The contention time of ReCo_f has a fixed duration that depends on the number of rounds s.

B. Time domain repeated contention

Repeated contentions can be implemented in the time domain by performing multiple back-off count-downs before each channel access. We refer to this version with ReCo_t. In this case, the m levels correspond to m intervals for resetting the back-off counter.

At each round, a backlogged station taking part in that round draws a random values between 1 and m, say i, and waits $i - 1$ back-off time slots before transmitting a *busy signal* in the i-th back-off slot, unless it hears a busy signal in back-off slot $j < i$. In the latter case, the station senses a busy signal transmitted by some other competing station(s). Hence, the tagged station stops its count down and drops out of the current contention phase. If instead the first $i - 1$ back-off time slots go by idle, then the tagged station transmits its busy signal in the i-th back-off slot. This action promotes the station to the next round. As long as carrier sensing works, all stations are aware of the end of the contention round.

The next round starts at the end of the back-off slot where the busy signal has been transmitted. Differently from ReCo_f, with ReCo_t the contention phase takes a variable time to complete, comprised between $s\delta$ and $ms\delta$, being δ the duration of a back-off slot. Although ReCo_t operation can possibly lead to contention times longer than legacy DCF, as discussed in the numerical results, the reduction on the collision probability can improve the channel utilization and the energy efficiency of the stations.

The top diagram in Fig. 1 illustrates a channel access example with two contention rounds in the time domain and $m = 10$. Five stations are competing for accessing the channel. Station B and E win the first contention since they transmit a busy signal first, at the fourth back-off slot, thus blocking the count down of all other stations. The next contention round (where only stations B and E are competing) starts immediately after. In the second and last round, the winning station B starts the channel activity phase at the beginning of the third back-off slot.

IV. Analysis of the contention procedure

The adoption of multiple contention rounds introduces a memory effect in the contention process, because the number of stations competing for the final channel access depends on the whole history of elimination rounds. The process can be modeled as a Markov process whose state, at a given contention round, represents the number of stations surviving up to that round.

Let n be the number of backlogged contending stations at the beginning of the contention phase, s be the number of rounds and m be the number of levels characterizing the scheme as described in § III. Let q_r denote the probability that a station picks level r, $r = 1, \ldots, m$. Let also $G_r = \sum_{j=r}^{m} q_j$ be the Complementary Cumulative Distribution Function (CCDF) associated to q_r. The probability that h stations survive after a single contention round, given that k stations are contending at the beginning of that round, is

$$P_{k,h} = \sum_{i=1}^{m-1} \binom{k}{h} q_i^h G_{i+1}^{k-h}, \quad h = 1, \ldots, k-1 \qquad (1)$$

and

$$P_{k,k} = \sum_{i=1}^{m} q_i^k \qquad (2)$$

We can form the $n \times n$ matrix $\mathbf{P}$ whose k-th row entries are $P_{k,h}$, for $h = 1, \ldots, k$, and 0 for $h = k+1, \ldots, n$ ($k = 1, \ldots, n$). $\mathbf{P}$ is the one-step transition probability matrix of a Markov chain $\mathcal{X}$ on the state space $\{1, 2, \ldots, n\}$ with an absorbing state at 1. The state probability vector at time t is denoted with $\mathbf{x}(t)$, $t \geq 0$, where $x_i(t) = \mathcal{P}(\mathcal{X}(t) = i), i = 1, \ldots, n$. It is $\mathbf{x}(0) = [0 \ldots 0\ 1]$, i.e., at the initial time $t = 0$ the Markov chain is in state $\mathcal{X} = n$ with probability 1.

The probability distribution of the number $\mathcal{W}$ of winning stations that survive through the s contention rounds is $\mathcal{P}(\mathcal{W} = h) = \mathcal{P}(\mathcal{X}(s) = h) = x_h(s)$, $h = 1, \ldots, n$, with $\mathbf{x}(s) = \mathbf{x}(0)\mathbf{P}^s$. We have a success after the completion of s rounds with probability $\mathcal{P}(\mathcal{W} = 1) = x_1(s)$.

Let $\mathbf{Q}$ denote the square matrix obtained by taking the last $n-1$ rows and columns of $\mathbf{P}$. $\mathbf{Q}$ is the one-step transition probability matrix of a transient Markov chain. Then, the collision probability p_c can be expressed as $p_c(s) = \mathcal{P}(\mathcal{W} > 1) = \mathbf{e}_1\mathbf{Q}^s\mathbf{e}$, for $s \geq 1$; $\mathbf{e}$ is a column vector of ones of size $n-1$, $\mathbf{e}_1$ is a row vector of size $n-1$ whose entries are $e_1(j) = 0$ for $j \neq n-1$ and $e_1(n-1) = 1$.

The matrix $\mathbf{Q}$ is lower triangular, with diagonal elements given by the right hand side of eq. (2) for $k = 2, \ldots, n$. Hence, its dominant eigenvalue is $\eta \equiv Q_{11} = \sum_{i=1}^{m} q_i^2$. Since $\mathbf{Q}$ is also a non-negative matrix, the left and right eigenvectors $\mathbf{v}$ and $\mathbf{u}$ associated to η are positive. Then, the asymptotic behavior of the collision probability as $s \to \infty$ can be written as $p_c(s) \sim \kappa\eta^s$, where $\kappa = \mathbf{e}_1\mathbf{uve}$.

We can state this result as follows: the collision probability decays geometrically as the number of rounds s grows, with a decay rate $\eta = \sum_{i=1}^{m} q_i^2$. Note that η is minimized for $q_i = 1/m$, $i = 1, \ldots, m$, i.e., when the level selection probability distribution is uniform. In that case it is possible to find closed forms for the dominant eigenvalue and associated eigenvectors of $\mathbf{Q}$. It is $\eta = 1/m$, $\mathbf{v} = [1\ 0\ \ldots\ 0]$ and $\mathbf{u} = [2\ 3\ \ldots\ n]^T/2$. Hence the asymptotic expansion of the collision probability is $p_c(s) \sim n/(2m^s)$ as $s \to \infty$. We have also:

$$p_c(s) = \mathbf{e}_1\mathbf{Q}^s\mathbf{e} \leq \mathbf{e}_1\mathbf{Q}^s\mathbf{u} = \frac{1}{m^s}\mathbf{e}_1\mathbf{u} = \frac{n}{2m^s} \qquad (3)$$

since all involved vectors and matrices are made up of non-negative entries and it is $\mathbf{e} \leq \mathbf{u}$, where the inequalities are meant to be entry-wise. Then, an asymptotically tight upper bound for the collision probability is

$$\hat{p}_c(s) = \min\left\{1, \frac{n}{2m^s}\right\}, \qquad s \geq 1 \qquad (4)$$

It is apparent from eq. (4) that the collision probability drops quickly as s is increased, the more the bigger m. As a matter of example, if we require that the collision probability be no bigger than 10^{-4}, it can be easily checked that $s = 4$ is enough with $m = 32$ for whatever value of $n \leq 200$.

As for the accuracy of the upper bound, we note that for $s = 1$ we do not need any approximation, since the collision probability can be calculated explicitly as:

$$p_c(1) = 1 - P_{n,1} = 1 - \frac{n}{m}\sum_{i=1}^{m-1}\left(\frac{i}{m}\right)^{n-1}, \quad n > 1 \qquad (5)$$

TABLE I
MINIMUM VALUE OF m SUCH THAT THE RELATIVE ERROR ε_p IS LESS THAN 0.15 FOR ALL $m \geq m_{min}$, FOR ANY n BETWEEN 2 AND 50.

s	2	3	4	5	6+
m_{min}	8	4	3	3	2

TABLE II
MAXIMUM RELATIVE ERROR ε_p FOR n RANGING BETWEEN 2 AND 50 FOR VARIOUS VALUES OF m AND s.

m	$s=2$	$s=3$	$s=4$	$s=5$	$s=6$	$s=7$
2	0.3941	0.4253	0.4406	0.3267	0.1447	0.0680
3	0.4287	0.4042	0.1114	0.0348	0.0113	0.0037
4	0.4406	0.1447	0.0329	0.0080	0.0020	0.0005
5	0.4460	0.0697	0.0132	0.0026	0.0005	0.0001
6	0.2829	0.0393	0.0063	0.0011	0.0002	0.0000
7	0.1963	0.0244	0.0034	0.0005	0.0001	0.0000
8	0.1447	0.0162	0.0020	0.0002	0.0000	0.0000

We define the relative error $\varepsilon_p \equiv (\hat{p}_c - p_c)/p_c$. Tab. I reports the values of m_{min} for all values of $s \geq 2$ such that $\varepsilon_p < 0.15$ for any n ranging between 2 and 50, while Tab. II quantifies the maximum error for different m values. For all practically interesting values of m and s, the upper bound (4) is very accurate and can be safely used for the dimensioning of the access protocol parameters.

The tight bound of the collision probability gives insight on why the repeated contention procedure is expected to be superior to "linear" CSMA. The maximum number of contention back-off slots for the time domain implementation is $m \cdot s$. Since CSMA performs a *single* contention round, its collision probability goes as $p_c^{CSMA} \sim 1/(ms)$, whereas the repeated contention procedure attains $p_c^{RECO} \sim 1/m^s$ for *the same contention time overhead in terms of maximum number of back-off slots in case of ReCo_t, much less time contention overhead for ReCo_f.*

The analysis of the collision probability applies to both frequency and time domain procedures, while the duration of the contention phase is different. Let B denote the number of back-off slots required to complete the contention phase. With frequency domain, the contention phase is made up of a fixed number s of rounds. If we assume that a contention round lasts one back-off slot, then $E[B] = s$. With time domain, let us consider a tagged round where k stations are contending. The probability that i back-off slots are counted is:

$$\sum_{h=1}^{k} \binom{k}{h} q_i^h G_{i+1}^{k-h} = G_i^k - G_{i+1}^k, \quad i = 1, \ldots, m-1, \tag{6}$$

and $q_m^k = G_m^k$ for $i = m$. The mean number of back-off slots counted down is $\sum_{i=1}^{m-1} i\,(G_i^k - G_{i+1}^k) + m\,G_m^k = \sum_{i=1}^{m} G_i^k$. The probability of having k contending stations at the end of round j has been denoted with $x_k(j)$. Let also $x_k(0)$ be the probability of having k contending stations at the beginning of the contention phase. Then, the mean of the number B of back-off slots required by s rounds is:

$$\mathrm{E}[B] = \sum_{j=0}^{s-1} \sum_{k=1}^{n} x_k(j) \sum_{i=1}^{m} G_i^k \tag{7}$$

A. Activity times

Fig. 1 shows the system time evolution as a sequence of contention and activity times. The duration A_s (A_c) of successful (collision) activity times can be represented as sum of two contributions: (i) overhead time $T_{oh,x}$ ($x = s, c$) accounting for PHY/MAC overhead and inter-frame spacings; (ii) payload transmission time.

Let $\mathcal{W}$ denote the number of stations that transmits concurrently and U_i is a random variable representing the time the frame payload takes to be transmitted by the i-th station. Then, we can write $A_s = T_{oh,s} + U_1$ in case $\mathcal{W} = 1$, and $A_c = T_{oh,c} + \max\{U_1, U_2, \ldots, U_{\mathcal{W}}\}$ for $\mathcal{W} > 1$. It is $U = L/R$, R being the air bit rate of the MAC interface and L the MAC PDU payload length. Both quantities take a discrete spectrum of values, so that we model U as a discrete random variable. Let $U \in \{a_1, a_2, \ldots, a_\ell\}$ with $a_1 \le a_2 \le \cdots \le a_\ell$, and $Q_j = \mathcal{P}(U \le a_j)$ for $j = 1, \ldots, \ell$. For notation convenience we set also $Q_0 = 0$. By the independence assumption, the payload times U_i are independent of one another, so it is straightforward to check that $\mathcal{P}(\max\{U_1, \ldots, U_r\} \le a_j) = Q_j^r$ ($j = 1, \ldots, \ell$), and $\mathrm{E}[\max\{U_1, \ldots, U_r\}] = \sum_{j=1}^{\ell} a_j (Q_j^r - Q_{j-1}^r)$, for $r \ge 1$. Specifically, we have $\mathrm{E}[U] = \sum_{j=1}^{\ell} a_j (Q_j - Q_{j-1})$. Letting $v_h = \mathcal{P}(\mathcal{W} = h)$, for $h = 1, \ldots, n$, the average activity times in case of successful transmissions or collisions are given by:

$$E[A_s] = T_{oh,s} + \sum_{j=1}^{\ell} a_j (Q_j - Q_{j-1}) = T_{oh,s} + \mathrm{E}[U] \tag{8}$$

$$E[A_c] = \frac{\sum_{k=2}^{n} v_k \sum_{j=1}^{\ell} (T_{oh,c} + a_j)(Q_j^k - Q_{j-1}^k)}{\sum_{k=2}^{n} v_k} \tag{9}$$

B. Saturation throughput

We evaluate the saturation throughput ρ for n stations continuously backlogged. By considering that the end of each activity time is a regeneration instant for the repeated contention procedure, we can express the normalized saturation throughput of ReCo as the ratio of the mean time spent to transmit the payload of a successful frame and the average duration of the regeneration cycle:

$$\rho_{ReCo} = \frac{(1 - p_c)\mathrm{E}[U]}{\mathrm{E}[C] + (1 - p_c)\mathrm{E}[A_s] + p_c \mathrm{E}[A_c]} \tag{10}$$

where $\mathrm{E}[C]$ is the average duration of the contention phase, p_c is the collision probability, $\mathrm{E}[U]$, $\mathrm{E}[A_s]$ and $\mathrm{E}[A_c]$ are given in eqs. (8) and (9). The expression is valid for both the frequency and time domain, with the only difference that the contention phase is constant and equal to $s \cdot \delta$ for ReCo_f, while it is random with average value $\mathrm{E}[B] \cdot \delta$ for ReCo_t.

As reference comparison terms, we also consider the throughput achievable under legacy DCF and under perfect scheduling. For the legacy DCF, the normalized throughput ρ_{DCF} can be found as a simple generalization of the model proposed in [22][23]:

$$\rho_{DCF} = \frac{P_s \mathrm{E}[U]}{P_e \delta + P_s T_{oh,s} + P_c T_{oh,c} + \sum_{j=1}^{\ell} a_j (Y_j - Y_{j-1})}$$

where δ is the back-off slot time, τ is the transmission probability in each channel slot, $Y_j = (1 - \tau + \tau Q_j)^n$, $j = 0, 1, \ldots, \ell$ and $P_e = (1 - \tau)^n$, $P_s = n\tau(1 - \tau)^{n-1}$, $P_c = 1 - P_e - P_s$. The probability τ can be found given the number n of stations, the DCF maximum retry parameter, M, and the contention window sizes, $W_i, i = 0, 1, \ldots, M$, by solving a non-linear equation system (see [22][23]), namely

$$\begin{aligned} \tau &= \frac{1 + p + p^2 + \cdots + p^M}{\beta_0 + \beta_1 p + \beta_2 p^2 + \cdots + \beta_M p^M} \\ p &= 1 - (1 - \tau)^{n-1} \end{aligned}$$

with $\beta_i = (W_i + 1)/2$ for $i = 0, 1, \ldots, M$.

In case of centralized scheduling, no contention and back-off are required and channel cycle is devoted to a successful transmission. Then

$$\rho_{ideal} = \frac{\mathrm{E}[U]}{T_{oh,s} + \mathrm{E}[U]} \tag{11}$$

C. Optimization of the contention parameters

In this section we give guidelines to the choice of m and s for maximizing the throughput of ReCo. Replacing $\mathrm{E}[A_c]$ in eq. (10) with an upper bound $T_{c,max}$ (e.g., the maximum allowed TxOP time) and p_c with the upper bound $\hat{p}_c$ given in eq. (4), we obtain a lower bound of the throughput:

$$\rho_{ReCo} \ge \rho_{lb} = \frac{(1 - \hat{p}_c)\mathrm{E}[U]}{\mathrm{E}[C] + (1 - \hat{p}_c)\mathrm{E}[U] + \hat{p}_c T_{c,max}} \tag{12}$$

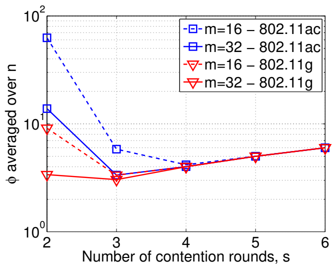


Fig. 2. The function ϕ for ReCo_f versus s, averaged over n for $20 \leq n \leq 200$, for two values of m (16 and 32) and two values of the parameter a, $a \approx 24$ (IEEE802.11g) and $a \approx 220$ (IEEE 802.11ac).

Maximizing ρ_{lb} is equivalent to minimizing the following function of s and m:

$$\phi(s, m; n) = \frac{\mathrm{E}[C] + \hat{p}_c T_{c,max}}{1 - \hat{p}_c} \tag{13}$$

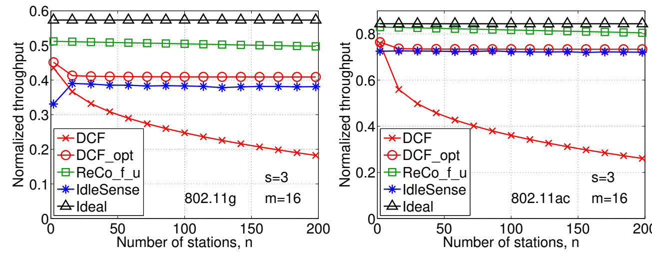
The only parameter that depends on the frame formats, timing, bit rate and other details of the protocol is the ratio $a \equiv T_{c,max}/\delta$. Given a, the quantity ϕ depends only on s and m and on the number of contending stations n. For ReCo_f we have

$$\phi_f(s, m; n) = \frac{s + a\frac{n}{2m^s}}{1 - \frac{n}{2m^s}} \tag{14}$$

for all values of s, m, n such that $n < 2m^s$. It is apparent that ϕ_f is monotonously decreasing with m. The limit on m is posed by practical feasibility of the radio hardware. As an example, let us consider the range $2 \leq n \leq 200$ and two relatively small values of m, namely 16 and 32. The values of ϕ averaged over the considered range of n is displayed in Fig. 2 as a function of s, for two values of a, i.e., $a \approx 24$ (a value consistent with IEEE 802.11g) and $a \approx 220$ (consistent with IEEE 802.11ac). It is seen that $s = 3$ is optimal except of the case $m = 32$ and IEEE 802.11ac, where $s = 4$ is better. The reason why of this weak dependance of the optimal level of s on the number of contending stations is highlighted by the expression of the optimal s^*, provided that the collision probability is small. In that case, it can be found easily that $s^* = \log_2(n\, a \log(m)/2)/\log_2(m)$. hence, s^* grows only with the logarithm of n.

V. Numerical Examples

We consider different examples based on the IEEE 802.11g and 802.11ac PHY parameters. As for IEEE 802.11g, we have $\delta = 20$ μs, 52 OFDM sub-carriers (20 MHz channel), data rate equal to 54 Mbps, and $T_{oh,s} = T_{oh,c} = 142.8$ μs (due to preambles, headers and acknowledgments). With IEEE 802.11ac, we consider $\delta = 9$ μs, 108 OFDM sub-carriers (40 MHz channel), data rate equal to 200 Mbps (1 spatial stream, 256-QAM with code rate 5/6), and $T_{oh,s} = T_{oh,c} = 162.9$ μs. Payload lengths are uniformly distributed over the set $\{80, 1500, 2304\}$ bytes in case of 802.11g and over the set $\{80, 1500, 9000, 11454\}$ bytes in case of 802.11ac by also taking into account the aggregation of 4 MPDU. For the standard IEEE 802.11 DCF the contention window values are $W_i = \min(16 \cdot 2^i, 1024)$ for $i = 0, \ldots, 7$.



(a) (b)

Fig. 3. Normalized throughput vs. n: comparison among ideal (no collisions), ReCo_f with uniform tone selection probabilities, IdleSense and IEEE 820.DCF with standard and optimized contention window sizes.

ReCo performance have been compared with standard and optimized IEEE 802.11 DCF[1] (labelled as DCF_opt); an ideal MAC, with no collision and no contention time overhead; and Idle Sense [14]. The last one has been simulated, by implementing carefully the algorithm described in [14] for each values of n.

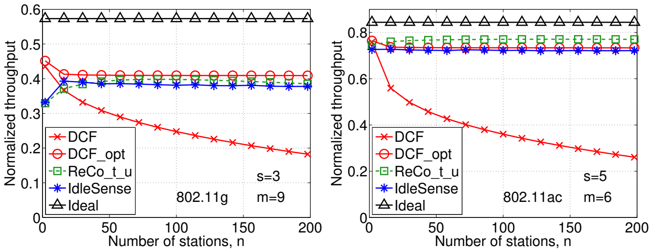
ReCo_f performance. In this case, the duration of each contention round is identified with the back-off slot duration.

Fig. 3 shows the normalized throughput ρ for $s = 3$ and $m = 16$ as a function of the number of contending stations n for the ideal MAC (triangle markers), ReCo_f with uniform tone selection probabilities (square markers), standard ('x' markers) and optimized (circle markers) IEEE 802.11 DCF and Idle Sense (asterisk markers). Figures 3(a) and 3(b) refer to IEEE 802.11g and to IEEE 802.11ac, respectively. The most relevant outcome is that ReCo_f exhibits close-to-ideal performance results, and that the achieved throughput is almost insensitive to the number of contending station in the range between 2 and 200. While Idle Sense exhibits excellent performance, except at small n levels, ReCo_f is definitely superior to both the optimized DCF and Idle Sense.

We observe that ReCo_f throughput performance are achieved with a *fixed* parameter configuration and a relatively small value of m. There is no need of implementing an estimator of the number of contending stations as in Idle Sense. This is a critical point whenever the offered traffic is volatile and intermittent, so that the number of contending stations varies quickly over time, possibly by large amounts. ReCo_f does not suffer the offered traffic variability, given that a *static* parameter setting is essentially optimal for n ranging between 2 and 200. This great advantage is gained at the price of being able of implementing reliably the tone detection while transmitting station's own tone, i.e., full-duplex radios.

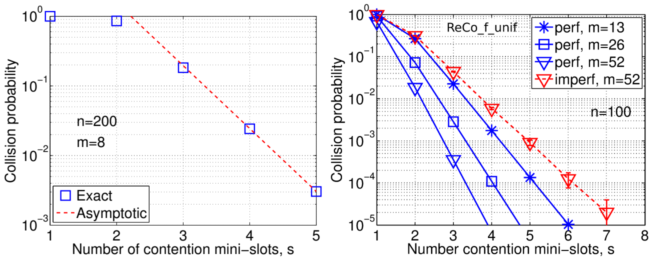
ReCo_t performance. The normalized saturation throughput is compared for the time domain contention procedure in Fig. 4 for the same protocols as in Fig. 3. The parameters m and s have been set to the values that minimize the contention overhead. It is apparent that ReCo_t performance are not so brilliant as those of the frequency domain counterpart, yet it still achieves (and sometimes improves on) the best

[1] Optimization of DCF maximizes the saturation throughput as a function of τ for each value of n, i.e., the contention window is chosen optimally and exponential back-off is suppressed.



(a) (b)

Fig. 4. Normalized throughput vs. n: comparison among ideal (no collisions), ReCo_t with uniform back-off selection probabilities, IdleSense and IEEE 802.11g/ac DCF with standard and optimized contention window sizes.



(a) (b)

Fig. 5. (a) Asymptotic expansion of the collision probability as a function of the number s of contention rounds; (b) collision probability vs s with perfect and imperfect tone detection.

performance yielded by the optimized DCF and Idle Sense. This is obtained with a *static* parameter configuration.

Collision probability. Fig. 5(a) shows the asymptotic tight upper bound of the collision probability (dashed line) against the exact value (square markers) for a generic ReCo scheme. The asymptotic bound lends itself to a simple and accurate dimensioning of the parameter s.

Imperfect round detection. We finally consider the impact of carrier sense errors for ReCo_t or full duplex errors for ReCo_f, which prevent some stations from correctly detecting the end of a contention round. Fig. 5(b) shows the graphs of p_c for uniform probability distribution of the contention level selection, with $n = 100$ stations and $m = 13$, 26 and 52. Solid lines refer to perfect round detection, while imperfect detection is shown with a dashed line with triangle markers. Imperfect detection has been modeled for ReCo_f by assuming the same error probabilities given in Fig. 11(c) of [9] with $SNR = 12\ dB$. The collision probability in case of round detection errors (red curve) has been obtained by simulation, together with the 95-level confidence intervals. It is apparent that imperfect reliability affects the performance of the ReCo access procedure, yet very low collision probability levels can still be achieved with few contention rounds. For example, for guaranteeing a collision probability lower than 10^{-4}, it is required to increase the contention rounds from $s = 4$ (ideal case) to $s = 7$ (imperfect case).

VI. Experimental Validation

In order to validate the ReCo performance in a real wireless network, we implemented the contention procedure in the time domain on commercial off-the-shelf 802.11g cards. Indeed, the time domain version of the scheme does not require hardware primitives which are not supported by off-the-shelf cards, because it is based on the repetition of back-off extractions and count-downs, transmission of short control frames at the end of the round, and sensing of the channel. All these primitives are supported by standard DCF, whose contention logic is usually implemented at the firmware level. Rather than working with an open firmware, we decided to exploit the high-level programming language exposed by the Wireless MAC Processor architecture (WMP) [11]. A firmware implementing this architecture with a generic executor of state machines has been developed for a commercial card by Broadcom and is publicly available, together with a graphical editor for programming state machines and a control interface for loading them inside the card.

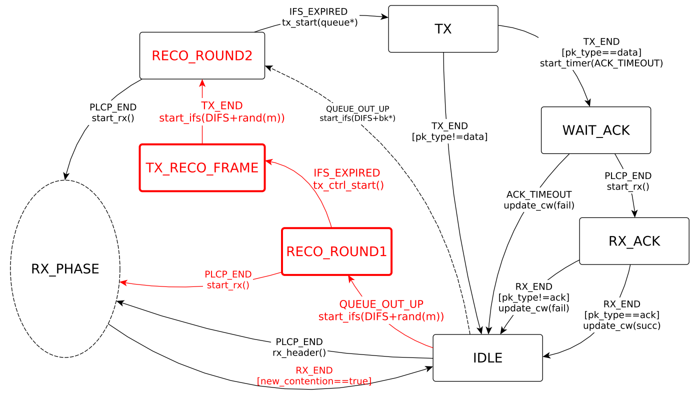


Fig. 6. State machine implementation of ReCo_t MAC program

A. ReCo_t implementation on the WMP platform

WMP Programming Language and Interface. In the WMP architecture, MAC protocols are defined in terms of state machines working on a set of pre-defined *actions*, *events* and *conditions* that can be supported by the hardware. Examples of actions are arithmetic operations, management of input and output queues, frame forging, as well as hardware functions for starting frame transmissions or setting a timer. Events include hardware interrupts, such as channel up signals, indication of reception of a valid preamble or end of a valid frame, expiration of timers and signals conveyed from the higher layers, such as the queuing of a new packet. Conditions are boolean expressions evaluated by comparing the card internal registers or the frame fields with a given parameter. The complete list of actions, events and conditions available for the current WMP implementation is described in [11] and represents the MAC programming interface. Non standard MAC protocols, including multi-channel schemes [11], moderated back-off [24], MetaMAC [25], etc., have been implemented and demonstrated by using the WMP API.

ReCo_t state machine. The ReCo_t state machine has been programmed by modifying a reference MAC program which implements a simplified DCF version. Fig. 6 shows a graphical representation of the ReCo_t state machine with two contention rounds (but generalization are straightforward), by enlightening the modifications on the original DCF program: additional states and transitions are shown in red, while one original transition removed from the program is shown with a dashed line. For sake of readability, the figure also groups

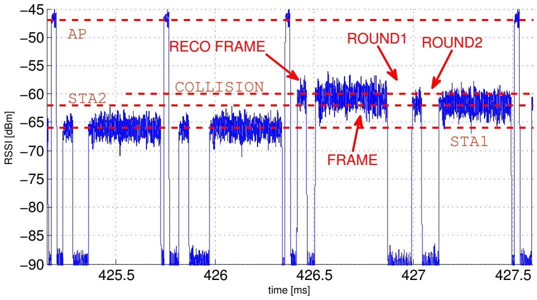
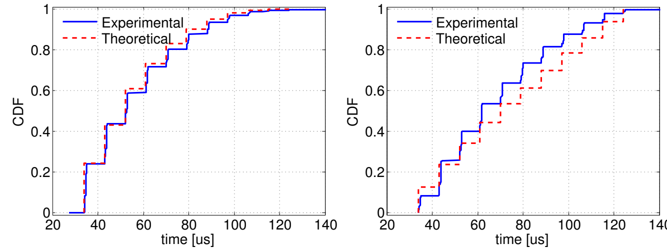


Fig. 7. Channel trace acquisition during traffic session when WMP ReCo implementation is active

the protocol states describing the reception operations into a single macro state (RX_PHASE). The operation of the program is somehow intuitive, but we detail the description of the modified contention mechanism. Starting from an IDLE state, the program switches to a RECO_ROUND1 state when a frame is ready in the transmission queue. The availability of a frame in the queue is signaled by the QUEUE_OUT_UP event. The back-off waiting time is set to a random value uniformly extracted in the range $(0, m-1)$. The back-off decrement is performed by the hardware action *start_ifs(DIFS+rand(m))*. It automatically waits for a DIFS idle time, decrements the waiting time of one unit at each subsequent idle slot, stops the decrement when the medium is busy (leaving the contention) or moves to the transmission of the busy signal (called ReCo control frame) and to the next contention round in case the back-off is reset to 0. Similar operations are performed from the RECO_ROUND2 state, from which the data frame transmission is started in case the back-off reaches 0. A new contention starts from the IDLE state after a transmission attempt or after the detection of a frame different from the ReCo control frame.

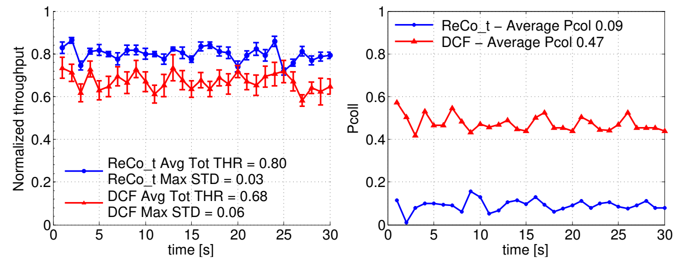
Functional validation. For demonstrating the behavior of the commercial 802.11g card by Broadcom once the ReCo_t state machine is loaded, we acquired a channel occupancy trace by using a software defined radio (namely, the USRP) as a channel sampling instrument. Fig. 7 shows a power level trace obtained in an experiment with three contending nodes transmitting at 36Mbps, $s = 2$ and $m = 11$. We can easily recognize idle times (low RSSI values of about -90dBm) and busy times (high RSSI values), as well as identify contention rounds ended with the transmission of a short control frame (called ReCo frame), and activity phases including data frame and acknowledgment transmissions. The ReCo frame is a non-standard frame lasting about $40\mu s$, i.e. as a ACK frame transmitted at 6 Mbps.

In the same experiment, we processed more than 3000 contentions for measuring the duration of the first and second contention round. Fig. 8 shows the cumulative distribution function of the inter-frame time preceding the transmission of ReCo control frames (a) and data frames (b). The possible values are in the range between the minimum inter-frame space equal to a DIFS (i.e. $34\mu s$) and the maximum space equal to a DIFS plus 11 back-off slots (i.e. $34 + 11 \cdot 9 = 133\mu s$). In the first round the distribution is given by the minimum



(a) (b)

Fig. 8. Cumulative distribution function for round 1 (a) and round 2 (b) in WMP ReCo implementation, with 3 stations and 802.11g.



(a) (b)

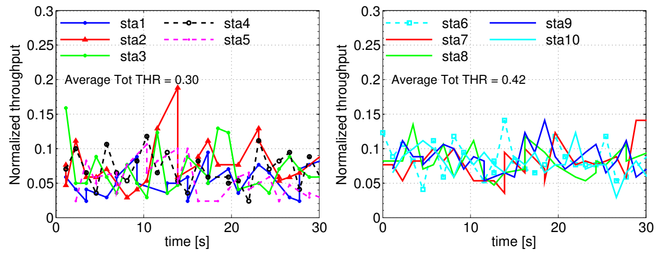
Fig. 9. Experimental throughput (a) and collision (b) probability results of DCF (red curve) and ReCo_t (blue curve) with 10 contending stations, 802.11g PHY and data rate equal to 6Mbps.

of three uniform distributions, while in the second round the distribution is almost a uniform distribution with 11 possible values, because in most cases only one station survives to the first contention. The mismatch between the theoretical and experimental results in the second round is given by imperfect round detection (not considered in the analysis).

B. Performance Results

We run several experiments in our testbed, in which 10 nodes based on the WMP platform are able to run both the DCF and ReCo_t state machines. In all the experiments, the network has been configured in infrastructure mode. Wireless nodes are built by using Linux-based embedded systems equipped with a 802.11g card by Broadcom and UDP *iperf* clients for generating the traffic towards the Access Point. Source rates have been configured for assuring saturation conditions with data packets of 1500 bytes and a data transmission rate of 6Mbps. The duration of the experiment is 30 seconds.

Fig. 9(a) shows the total normalized throughput achieved with 10 contending stations in case of legacy DCF and ReCo_t. The ReCo_t scheme has been configured with $m = 11$ and $s = 2$. The total normalized throughput is 68% for DCF and 80% for ReCo_t. Although with these settings ReCo_t spends more time than legacy DCF in contention (namely about 0.6 slot in the first round and 4.2 slots in the second round plus two DIFS intervals, versus 1.7 slots and one DIFS for DCF), it is more efficient than DCF because of the significant reduction of the collision rate (as shown in Fig. 9(b)). The average collision probability perceived with DCF is 47.43% (38.8% according to the model in [22]), while such a value is only 8.94% with ReCo_t (7.9% with the ReCo model). Furthermore, for ReCo_t the throughput results exhibit low variability among the stations, as quantified in the bars shown in Fig. 9(a).



(a) (b)

Fig. 10. Experimental throughput results in scenario with heterogeneous contention protocols: 5 DCF stations (a) and 5 ReCo_t nodes (b).

For proving the compatibility of the ReCo_t scheme with legacy DCF, we performed a last experiment in which contending stations running different contention programs coexist. Indeed, DCF stations can coexist with ReCo_t stations, although the effect of ReCo control frames is different for the two protocols: DCF stations just freeze their back-off counter until the ReCo control frame is transmitted, while ReCo_t stations abandon the contention until a subsequent data frame is received. Moreover, since DCF stations do not leave the contention at the end of each ReCo_t contention round, ReCo_t stations experience higher collision rates than in the case of homogeneous ReCo_t stations. The residual collision probability cannot be simply controlled by working on s and m, because it also depends on the number of DCF stations. Fig. 10 plots the throughput results in a reference scenario with 5 legacy DCF stations (a) and 5 ReCo_t stations (b), for the same $s = 2$ and $m = 11$ settings used in the previous experiment. The normalized throughput perceived by each station is comparable with the previous scenarios with homogeneous contention rules. The total normalized throughput is 30% for DCF stations (slightly lower than one half of the previous 68% result) and 42% for ReCo_t stations.

VII. Discussion and Conclusions

We have presented ReCo, a random access scheme based on repeated contention rounds for emerging wireless technologies (supporting full-duplex radio or MAC logic reconfigurations). Despite of its simplicity, ReCo offers stable and close-to-ideal throughput performance. It can be dimensioned with reliable and simple formulas for outperforming legacy DCF (in the case of ReCo_f) or at least matching optimal DCF (in the case of ReCo_t) without requiring an estimation of the number of competing stations.

Further work can be directed to: (i) developing adaptive algorithm for sizing s as a function of the competing station number n; (ii) the possibility of defining an additional initial round to handle priorities or scheduling policies, (iii) parallel contention on multiple frequency bands, that can be combined, e.g., if a station wins in two contiguous 20 MHz channels, it can use them as a unique 40 MHz channel.

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