RCFD: A Novel Channel Access Scheme for Full-Duplex Wireless Networks Based on Contention in Time and Frequency Domains

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Abstract—In the last years, the advancements in signal processing and integrated circuits technology allowed several research groups to develop working prototypes of in-band full-duplex wireless systems. The introduction of such a revolutionary concept is promising in terms of increasing network performance, but at the same time poses several new challenges, especially at the MAC layer. Consequently, innovative channel access strategies are needed to exploit the opportunities provided by full-duplex while dealing with the increased complexity derived from its adoption. In this direction, this paper proposes the design of a MAC layer scheme for full-duplex ad hoc wireless networks, based on the idea of time–frequency channel contention. According to this approach, different OFDM subcarriers are used to coordinate nodes access to the shared medium. The proposed scheme leads to efficient transmission scheduling with the result of avoiding collisions and exploiting full–duplex opportunities. The considerable performance improvements with respect to standard and state–of–the–art MAC protocols for wireless networks are highlighted through both theoretical analysis and network simulations.

Index Terms—Full–duplex wireless, time–frequency channel access, orthogonal frequency–division multiplexing (OFDM), medium access control (MAC), IEEE 802.11

1 INTRODUCTION

Innovation in Medium Access Control (MAC) plays a crucial role in the evolution of wireless networks. The purpose of MAC protocols is to efficiently coordinate the use of a shared communication medium by a large number of users. Depending on the network architecture, the application and the target performance, MAC protocols may be designed and operate either in a centralized or in a distributed fashion. Currently implemented strategies are able to provide high throughput and acceptable fairness. However, their performance in terms of delay or efficiency (particularly when the payload size is small) is in general not desirable. Moreover, distributed MAC schemes for wireless networks generally suffer from several issues, such as the hidden terminal (HT) and exposed terminal (ET) problems, that may result in considerable performance degradation.

Many of these issues are related to inherent limitations of wireless networks, one of the most important being the so-called half–duplex (HD) constraint, i.e., the impossibility for a radio to transmit and receive in the same frequency band at the same time. Bidirectional communication is often facilitated by emulating full–duplex (FD) communication, using time–division duplex (TDD) or frequency–division duplex (FDD), at the expense of a reduction in achievable throughput. In the recent years, however, several research groups presented working prototypes of FD wireless systems [3], [4] that exploited advancements in analog circuit design and digital signal processing techniques to accomplish simultaneous transmission and reception in the same frequency band. These results were followed by further research efforts aimed at exploiting FD to enhance the overall network performance.

The possibility for a node to receive and transmit at the same time increases the nodes exposure to interference and considerably complicates the management of spatial reuse and scheduling of transmissions. Consequently, the design of new channel access schemes to efficiently exploit the FD capabilities and produce significant performance gains compared to currently deployed HD systems represents a very important and timely research topic and is the focus of this research. Assuming the use of orthogonal frequency division multiplexing (OFDM) as an efficient physical layer technology for communications over wideband wireless channels, here we specifically present a novel distributed MAC protocol which benefits from contention in both time and frequency domains.

In the sequel, we first briefly review the literature on full–duplex wireless MAC and contention resolution in the frequency domain and then present a summary of the contributions and the organization of this article.

1.1 Full–duplex wireless

The main challenge in achieving FD wireless communication is the self–interference (SI) in the receive chain when transmission and reception occur simultaneously. Indeed, due to the much shorter distance, the power of the signal emitted by a node at its own receiver is much higher than that of any other received signal.
This may prevent a successful reception when a transmission is taking place. Hence, high performance FD wireless communication may only be feasible when self–interference is effectively canceled.

While the first experimental tests concerned with SI cancellation date back to 1998 [5], only in 2010 did some research groups independently present the first working prototypes [3], [4]. The proposed methods exploited antenna placement, analog circuit design, digital domain techniques or a combination of these approaches with the aim of reducing the SI power to the noise floor level. A very good review of the state–of–the–art on FD wireless systems and SI cancellation techniques can be found in [7].

Several full–duplex MAC protocols for both infrastructure and ad hoc wireless networks have been reported in the scientific literature. A complete survey is available in [8]. In the infrastructure configuration, some schemes have been developed for the case of asymmetric traffic, that aim at identifying FD opportunities and solving HT problems, through either busy tones [9] or header snooping, shared backoff and virtual contention resolution [10]. In contrast to the centralized scheme proposed in [11], these works do not consider the interference between nodes. The authors in [12] proposed a power–controlled MAC, where the transmit power of nodes is adapted in order to maximize the signal–to– interference–plus–noise ratio of FD transmissions. More strategies are available for ad hoc networks, such as [13], which proposes a distributed scheduling protocol aimed at enhancing efficiency while preserving fairness among the scheduled links. To cope with asymmetric traffic, the works in [14] and [15] make use of Request To Send (RTS)/Clear To Send (CTS) packets to identify FD transmission opportunities. The MAC scheme proposed in [16] deals with contention resolution techniques to handle inter–node interference in FD networks. Other works propose solutions able to enhance the end–to–end performance in multi–hop FD networks, e.g., [17], where the use of directional antennas is addressed, [18], where frequency reuse to enhance outage probability is investigated, and [19], that proposes synchronous channel access. Finally, cross–layer approaches have been proposed, in which PHY layer techniques, such as node signatures [20] and attachment coding [2], are exploited to schedule transmissions in FD MAC schemes.

All the presented MAC protocols adopt a time domain approach to resolve contentions and identify FD communication opportunities. While largely adopted, this strategy generally relies on the exchange of additional control frames, thus decreasing the efficiency. Moreover, such class of MAC schemes often resort to random waiting intervals (backoffs) to avoid collisions and preserve fairness among users. This in turn increases the randomness in packet delay and hampers the ability to provision quality of service (QoS) guarantees.

### 1.2 Frequency–based channel access

In an attempt to overcome the limitations of standard channel access schemes for wireless networks in the time domain, researchers have proposed to move the channel contention procedure to the frequency domain [21]. Such an approach exploits OFDM modulation at the physical layer, which provides an ordered set of subchannels or subcarriers (SCs), equally spaced in frequency within a single wideband wireless channel. The idea is to let the nodes contend for the channel by randomly selecting one of these SCs and assign the channel to the node that has chosen, for example, the one with the lowest frequency. This resolves contention in a short deterministic time, even for a large number of nodes, compared to conventional time–domain schemes, such as the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol adopted by IEEE 802.11 networks. The approach was extended to handle multiple collision domains and selective fading in [22], where the backoff to frequency (BACK2F) protocol was introduced. A similar strategy was suggested in [23], where the set of available SCs is divided into two subsets, one destined to random contention and the other to node identification. Here the ACK procedure was also moved to the frequency domain, allowing a further improvement of the efficiency.

Although this approach is promising in that it resolves contentions in a deterministic amount of time, it still suffers from certain issues that affect MAC in wireless ad hoc networks, such as HT and ET. Moreover, none of the currently proposed frequency domain protocols is designed to handle channel access in FD wireless networks, while the availability of a large number of SCs in OFDM networks can be exploited to effectively identify and select FD opportunities. In addition, it has been suggested that FD communications could help limit the SC leakage problem, which affects the performance of MACs based on frequency domain contention [22].

### 1.3 Contributions and Organization of this Article

This paper proposes a MAC layer protocol for ad hoc FD wireless networks based on time–frequency contention that is capable of efficiently exploiting FD transmission opportunities and resolving collisions in a short and deterministic amount of time.

To this end, we propose a frequency domain MAC with multiple contention rounds in time, each using an OFDM symbol. This framework is exploited to advertise the nodes transmission intentions and to select, within each contention domain, the pair of nodes that will actually perform a data exchange. This strategy resembles the time–domain RTS/CTS often adopted in IEEE 802.11 networks [24], therefore we refer to it as RTS/CTS in the Frequency Domain (RCFD). The presented scheme is fully distributed, effectively handles multiple contention domains and preserves sufficient randomness to ensure fairness among different users. To the best of the authors’ knowledge, this is the first work that combines channel access in the time and frequency domains and applies it to FD wireless networks.

To assess the performance of the proposed RCFD MAC protocol and compare it against the state–of–the–art, we present both theoretical analysis and simulation results. As a first step, we theoretically analyze the saturation throughput of the RCFD protocol in a network with a single collision domain. To provide an effective benchmark, an original theoretical analysis of the MAC protocols proposed in [14] and [22] is developed. A further performance evaluation for the more general case with multiple collision domains is presented using network simulations. Again, the performance of RCFD is compared with that of state–of–the–art MAC protocols, that have been purposely implemented in the same simulation platform.

The proposed approach is able to take the best out of the two strategies previously presented, namely time–domain and frequency–domain contention. Indeed, compared to frequency–domain MAC protocols, such as [22], the proposed scheme allows to eliminate the HT issue, exploiting the multiple round RTS/CTS procedure. Moreover, compared against previously reported time–
domain MAC protocols for FD wireless networks, such as [14]. RCFD exhibits an increased efficiency as well as a reduced delay.

The rest of the paper is organized as follows. The new RCFD MAC protocol is presented in Section 2, together with some examples of its operation. Section 3 contains a theoretical analysis of this strategy and several related wireless MAC protocols from the literature. In Section 4, the proposed protocol is evaluated using network simulations. Section 5 discusses the assumptions we made during protocol design and some possible optimizations. Finally, Section 6 concludes the paper and outlines some future directions of research.

2 The RCFD Full-duplex MAC Protocol

The RCFD algorithm is a channel access scheme based on a time and frequency domain approach. According to this strategy, not only the medium contention, but also transmission identification and selection are performed over multiple consecutive frequency domain contention rounds. In this section we describe the simplest version of this protocol, deferring a discussion of possible enhancements to Section 5.

2.1 System model

The RCFD is designed for an ad hoc wireless network composed of $N$ nodes with the same priority. Each node is assumed to have perfect FD capabilities, i.e., it can simultaneously receive a signal while transmitting in the same frequency band with perfect self-interference cancellation. OFDM is adopted at the physical layer to transmit consecutive symbols over a set of $S$ subcarriers. During the channel contention phase only, nodes transmit on single SCs while listening to the whole channel. In the data transmission phase, instead, only one pair of nodes transmit and receive in each collision domain, exploiting all SCs available in the selected channel, as generally done in existing IEEE 802.11 networks [24].

The proposed protocol relies on some assumptions that ensure its correct behavior. The validity of these assumptions as well as the possibility of relaxing them will be discussed in Section 5. We first suppose that all nodes have data to send and try to access the channel simultaneously. The communication channel is assumed ideal (no external interference, fading or path loss), so that each node can hear every other node within its coverage range. There can be multiple collision domains, i.e., the range of a node may not include all the nodes in the network.

We assume that a unique association between each node and two OFDM subcarriers is initially established at network setup, maintained fixed throughout all operations and available to each node. More specifically, defining $S = \{s_1, \ldots, s_S\}$ as the set of available SCs, we split it in two non-overlapping parts $S_1$ and $S_2$. Taking $N = \{n_1, \ldots, n_N\}$ as the set of network nodes, a mapping is defined by the two functions

$$\mathcal{T}_1 : N \rightarrow S_1, \quad \mathcal{T}_2 : N \rightarrow S_2$$

(1)

that uniquely link any node with an associated SC in each set. A simple implementation of such a map can be obtained by taking $S_1 = \{s_1, \ldots, s_{S/2}\}$, $S_2 = \{s_{S/2+1}, \ldots, s_S\}$ and defining $\mathcal{T}_1(n_i) = s_i$, $\mathcal{T}_2(n_i) = s_{i+S/2}$, $i = 1, \ldots, N$. It is worth stressing that the correspondence between a node and each of the two SCs must be unique, i.e., $\mathcal{T}_1(n_i) \neq \mathcal{T}_1(n_j)$ and $\mathcal{T}_2(n_i) \neq \mathcal{T}_2(n_j)$ for every $i \neq j$.

Finally, it has to be noted that the assumed mapping imposes a constraint on the number of nodes in the network. Indeed, since each node must be uniquely associated with two OFDM SCs, the total number of nodes has to be less than or equal to $S/2$.

2.2 Channel contention scheme

The channel access procedure is composed of three consecutive contention rounds in the frequency domain. The first round starts after each node has sensed the channel and found it idle for a certain period of time $T_{scan}$. Each round consists in the transmission of an OFDM symbol and its duration is set to $T_{round} = T_{sym} + 2T_p$ to accommodate for signal propagation, which takes a time $T_p$ each way [24]. Therefore, the access procedure takes a fixed time of

$$T_{acc} = T_{scan} + 3T_{round}$$

(2)

As an example, if an IEEE 802.11g network is considered, standard values for these parameters are $T_{scan} = 28 \mu s$ (the duration of a DCF inter-frame space interval), $T_{sym} = 4 \mu s$, and $T_p = 1 \mu s$, thus obtaining $T_{acc} = 46 \mu s$.

In the following we outline the steps performed by every node in each contention round.

2.2.1 First round - randomized contention

Every node that has data to send and has found the channel idle for a $T_{scan}$ period, randomly selects an SC from the whole set $S$ and transmits a symbol only on that SC, while listening to the whole channel band.

We denote with $\tilde{s}_i$ the SC chosen by node $n_i$, where $\tilde{s}_i = 0$ if node $n_i$ does not have data to send. We also indicate with $S^i_1$ the set of SCs that actually carried a symbol during the first contention round, as perceived by node $n_i$.

Node $n_i$ is defined as primary transmitter (PT) if and only if the following condition holds

$$\tilde{s}_i = \min_j \left[ s_j \in S^i_1 \right]$$

(3)

i.e., the lowest–frequency SC among those carrying data is the one chosen by the node itself. It is noteworthy that, in a realistic scenario of multiple collision domains, several nodes in the network can be selected as PTs. Moreover, if multiple nodes in the same collision domain pick the same lowest–frequency SC, they are all selected as PTs. This potential collision will be resolved in the following contention rounds.

2.2.2 Second round - transmission advertisement (RTS)

Only the nodes who identify themselves as PTs during the first round transmit during the second round. A PT node $n_i$ that has data to send to node $n_j$ transmits a symbol on two SCs, namely $s_{q} = \mathcal{T}_1(n_i) \in S_1$ and $s_{h} = \mathcal{T}_2(n_i) \in S_2$. In this way, $n_i$ informs its neighbors that it is a PT and has a packet for $n_j$. This round is the so-called RTS part of the algorithm, as it resembles the time domain RTS procedure defined in the IEEE 802.11 standard [24]. During the second round, all the nodes in the network (including the PTs) listen to the whole band. We denote as $S^i_2 \subseteq S_1$ and $S^i_{2,1} \subseteq S_2$ the sets of SCs that carried a symbol during the second contention round, as perceived by a generic node $n_i$.

Node $n_h$ is defined as RTS receiver (RR) if and only if the following condition holds

$$\mathcal{T}_2(n_h) \in S^i_{2,1}$$

(4)

i.e., at least one PT node advertised, during the second round, that it has a packet for $n_h$. There can be multiple RRs in the network, but a node cannot be both PT and RR at the same time, since, in order to be a PT, all the nodes within its coverage range must not be PT, i.e., they could not send an RTS.
2.2.3 Third round - transmission authorization (CTS)

Only the nodes selected as RRs during the second round transmit in the third one. Any RR node $n_b$ will select its CTS recipient as

$$n_i = \arg \min_{n_t} \{F_1(n_t) : F_1(n_t) \in S_{\text{h,1}}^2\}$$

(5)

i.e., among the nodes that have sent an RTS to $n_b$, the one with the lowest corresponding SC is selected. Node $n_b$ then transmits a symbol on two SCs, namely $s_i = F_1(n_b) \in S_1$ and $s_4 = F_2(n_b) \in S_2$. In this way, $n_b$ informs $n_i$ that its transmission is authorized. Since this round mimics the operation of the time domain CTS procedure, it is referred to as the CTS part of the RCFD algorithm. During the third round, all the nodes in the network (including the RRs) listen to the whole channel band. We denote as $S_{\text{h,1}}^1 \subseteq S_1$ and $S_{\text{h,2}}^1 \subseteq S_2$ the sets of SCs that carried a symbol during the third round, as perceived by a generic node $n_i$.

At the end of the third round, each node that has data to send needs to decide whether to transmit or not, according to the information gathered in the three rounds. Specifically, assuming a generic node $n_i$ which has a packet for node $n_j$, three cases can be distinguished:

I. **Node $n_i$ is a PT:**
   It transmits if and only if both these conditions are verified

   $$F_1(n_t) \in S_{\text{h,1}}^3$$

   $$S_{\text{h,1}}^3 = [F_2(n_i)]$$

   (6)

i.e., the intended receiver (node $n_j$) has sent a CTS and this is the only CTS within the contention domain of node $n_i$.

II. **Node $n_i$ is an RR:**
   It transmits (while receiving from the PT, thus enabling FD) if and only if both these conditions are verified

   $$S_{\text{h,1}}^3 = [F_1(n_j)]$$

   $$S_{\text{h,1}}^3 = [F_1(n_i)]$$

   (7)

i.e., only the intended receiver (node $n_j$) has sent an RTS and no other node has sent a CTS (except node $n_i$ itself).

III. **Node $n_i$ is neither a PT nor an RR:**
   It does not transmit.

We point out that not only the nodes selected as PTs during the first round may be granted access to the channels, but also an RR can transmit, if the conditions in case II are verified. This possibility is the key to enable FD transmission: a node that has a packet for another node from which it has received an RTS can send it together with the primary transmission (provided that no other CTSs from surrounding nodes were received).

2.3 Examples of operation

In order to better understand how the proposed MAC strategy works, we provide here two examples, for a simplified system with $N = 3$ nodes and $S = 6$ OFDM subcarriers. The simplest scheme is adopted for SC mapping, i.e., $S_1 = \{s_1, s_2, s_3\}$, $S_2 = \{s_4, s_5, s_6\}$, $F_1(n_i) = s_i$, $F_2(n_i) = s_{i+3}$, $i = 1, 2, 3$.

Two different example scenarios are considered. Fig. 1 and Fig. 2 show the contention rounds for scenarios 1 and 2, respectively, while Fig. 3 reports the network topology and the transmission intentions. In both scenarios, node $n_2$ is within the transmission range of nodes $n_1$ and $n_3$ that, however, cannot sense each other (two collision domains). In the first scenario, nodes $n_1$ and $n_3$ both intend to send a packet to $n_2$, resembling a typical HT situation. In the second one, nodes $n_1$ and $n_2$ have a packet for each other, representing a potential FD communication instance.

As seen in Fig. 1 for scenario 1, in the first round the two nodes with data to send randomly select two SCs as $\bar{s}_1 = s_4$ and
3 Theoretical analysis

In order to validate the proposed protocol and highlight the benefits it is able to provide, we compare its performance against those offered by standard MAC algorithms for wireless networks and other state–of–the–art strategies.

In this section we provide a theoretical comparison based on the analytical evaluation of the normalized saturation throughput of different MAC algorithms. This quantity is defined as the maximum load that a system is able to carry without becoming unstable [25]. It can also be seen as the percentage of time that nodes with full buffers can utilize the channel for data transmission using a contention–based MAC scheme. In order to provide meaningful results, some assumptions are made. We consider a network of \( N \) nodes, all within the same collision domain and with saturated queues, meaning that every node always has at least a packet to transmit. Furthermore, an ideal communication channel is assumed, so that the only cause of transmission errors would be collisions among different packets. Finally, we suppose that both the transmission rate \( R \) and the payload size \( L \) (in Bytes) are fixed.

We consider four different MAC layer algorithms to compare with our proposed RCFD strategy. The baseline scheme is the IEEE 802.11 Distributed Coordination Function (DCF) proposed in the standard [22], both with and without the RTS/CTS option. We selected the FD MAC strategy [14] among the various time–domain MAC protocols for FD networks discussed in Section 1.1 since it is one of the most general approaches, and does not impose any assumption on network topology, traffic pattern or PHY configuration. Finally, the BACK2F scheme [22] has been chosen as a protocol that performs channel contention in the frequency domain.

In order to obtain a fair comparison, all the algorithms are based on the same underlying physical layer, specifically that described by the IEEE 802.11g standard, which is very widespread. Tab. 1 reports the main parameters of this standard that are considered in this theoretical analysis.

### 3.1 Analysis for IEEE 802.11 and FD MAC

The starting point for the analysis is the work in [25], where the normalized saturation throughput was derived for the IEEE 802.11 DCF (with and without RTS/CTS). In this section we report the main results of that study and extend them to evaluate the normalized saturation throughput for the FD MAC algorithm [14].

We recall that the IEEE 802.11 DCF is based on a CSMA/CA strategy, where nodes listen to the channel before transmitting. If they find it busy, they wait until it becomes idle, and then defer transmission for an additional random backoff period in order to avoid collisions. The first analysis step is, hence, the introduction of a discrete–time Markov model to describe the behavior of a single station during backoff periods. This model was then used to derive the probability \( \tau \) that a single station transmits in a randomly chosen slot and the probability \( p \) that a transmission results in a collision, as functions of the system parameters, such as the initial value of the backoff window \( W \) and the maximum number of backoff stages \( m \). Subsequently, two probabilities were computed, namely \( P_\mu \), the probability that at least a transmission attempt takes place in a slot, and \( P_r \), the probability that this transmission is successful, expressed as functions of the number of nodes in the network \( N \), and of the probabilities \( \tau \) and \( p \). Specifically, the number of stations that transmit in a given slot is a binomial random variable \( B \) of parameters \( N \) and \( \tau \) and the probabilities \( P_\mu \) and \( P_r \) can be expressed as

\[
\begin{align*}
P_\mu &= P(B \geq 1) = 1 - (1 - \tau)^N \quad \quad (8) \\
P_r &= P(B = 1 | B \geq 1) = \frac{N\tau(1 - \tau)^{N-1}}{1 - (1 - \tau)^N} \quad \quad (9)
\end{align*}
\]

Finally, the saturation throughput can be computed as

\[
\eta_{DCF} = \frac{P_\mu P_r T_d}{(1 - P_\mu) T_{slot} + P_\mu P_r T_S + P_\mu (1 - P_r) T_C} \quad \quad (10)
\]

where \( T_d \) is the payload transmission time, \( T_{slot} \) is the slot time in IEEE 802.11, \( T_S \) is the slot duration in case of successful transmission and \( T_C \) is the slot duration in case of a collision. The values for \( T_S \) and \( T_C \) are, as computed in [25],

\[
\begin{align*}
T_S &= T_{dfs} + T_h + T_d + T_{sifs} + T_{ack} + 2T_p \\
T_C &= T_{dfs} + T_h + T_d + T_p
\end{align*}
\]

for the standard IEEE 802.11 DCF without RTS/CTS and

\[
\begin{align*}
T_S &= T_{dfs} + T_{rts} + T_{cts} + T_h + T_d + 3T_{sifs} + T_{ack} + 4T_p \\
T_C &= T_{dfs} + T_{rts} + T_p
\end{align*}
\]

### TABLE 1

| Parameter | Description | Value |
|-----------|-------------|-------|
| \( T_s \) | PHY and MAC header transmission time | 320 µs |
| \( T_{ack} \) | MAC–layer ACK transmission time | 135 µs |
| \( T_{rts} \) | RTS frame transmission time | 186 µs |
| \( T_{sifs} \) | CTS frame transmission time | 135 µs |
| \( T_{dfs} \) | Short Inter–Frame Space | 10 µs |
| \( T_{IFS} \) | DCF Inter–Frame Space | 28 µs |
| \( T_p \) | Propagation time over air | 1 µs |
| \( T_{slot} \) | MAC–layer slot time | 9 µs |
| \( W \) | Initial value of backoff window | 16 |
| \( m \) | Maximum number of retransmission attempts | 6 |
| \( S \) | Number of available OFDM subcarriers | 52 |
| \( T_{round} \) | Duration of a contention round in the frequency domain | 6 µs |
in case the RTS/CTS option is enabled. The meaning and the values of parameters \( T_{\text{diffs}} \), \( T_{\text{nifs}} \), \( T_{\text{rtr}} \), \( T_{\text{cts}} \), \( T_{\text{ack}} \) and \( T_p \) are reported in Tab. 1 whereas the payload transmission time \( T_d \) can be trivially computed as \((8 \cdot L)/R\).

The analysis just presented is extended to account also for the FD MAC algorithm, presented in [14]. This MAC protocol is very similar to the DCF with the use of RTS and CTS frames, with the only exception that a successful FD transmission can occur in two different cases. The first one is that only two nodes grab the channel simultaneously and have packets for each other, which occurs with probability

\[
P(B = 2|B \geq 1) = \frac{N \tau (1 - \tau)^{N-2}(2 - \tau)}{2(N - 1)(1 - (1 - \tau)^N)}
\]

(15)

since the probability that a generic node has a packet for another specific node is \(1/(N - 1)\). A successful FD communication takes place also if a single node grabs the channel, which happens with probability expressed by Eq. (3), and the target receiver has a packet for it at the head of the queue, which happens with probability \(1/(N - 1)\). Hence, the probability that a successful FD transmission takes place is given by

\[
P_{s,fd} = \frac{P(B = 2|B \geq 1) + P(B = 1|B \geq 1)}{(N - 1)^2} = \frac{N \tau (1 - \tau)^N - 2(1 - \tau)}{2(N - 1)(1 - (1 - \tau)^N)}
\]

(16)

A successful HD transmission happens when a single node grabs the channel but the target receiver does not have a packet for it, which occurs with probability

\[
P_{s,hd} = P(B = 1|B \geq 1) \left(1 - \frac{1}{N - 1}\right) = \frac{N(N - 2) \tau (1 - \tau)^{N-1}}{(N - 1)(1 - (1 - \tau)^N)}
\]

(17)

Consequently, the saturation throughput is given by

\[
\eta_{FD} = \frac{T_d P_{tr} P_{s,hd} + 2T_d P_{tr} P_{s,fd}}{(1 - P_{tr}) T_{\text{slot}} + P_{tr} T_S + P_{tr} (1 - P_{tr}) T_C}
\]

(18)

where \( P_{tr} \), \( T_S \) and \( T_C \) are expressed by Eq. (9), (12) and (14) respectively.

### 3.2 Analysis for frequency–based access strategies

The Markov model introduced in [25] is no longer useful with channel access schemes that do not rely on a time–domain contention approach, such as the BACK2F described in [22] and the RCFD proposed in this paper. The main difference is that there are no backoff periods anymore and, hence, the computation of probabilities \( P_{tr} \) and \( P_S \) needs to follow a different approach.

In the case of the BACK2F scheme, there cannot be idle slots (i.e., \( P_{tr} = 1 \)) and the only case in which a transmission is not successful is when there is a collision on the SC selection, which happens with probability \( P_{\text{coll}} \), i.e., \( P_s = 1 - P_{\text{coll}} \). In this scheme two contention rounds are considered in order to mitigate such an issue as much as possible. The probability that, at the first round, the \( j \)-th SC is selected by \( i \) nodes and the other \( N - i \) nodes select higher–frequency SCs among the \( S - j \) available is \( \binom{N}{i} \left( \frac{1}{S} \right)^i \left( \frac{S - j}{S} \right)^{N-i} \). Therefore, the probability that exactly \( i \) nodes collide in the first round is

\[
P(i) = \sum_{j=1}^{S} \binom{N}{i} \left( \frac{1}{S} \right)^i \left( \frac{S - j}{S} \right)^{N-i}
\]

(19)

Only the nodes that have collided in the first round take part in the second round, hence the probability that \( k \) nodes collide in the second round given that \( i \) nodes have collided in the first one is

\[
P(k|i) = \sum_{j=1}^{i} \binom{i}{j} \left( \frac{S - j}{S} \right)^{N-i}
\]

(20)

Finally, the collision probability can be computed as the probability that at least two nodes collide in the second round, that is

\[
P_{\text{coll}} = \sum_{i=2}^{N} \sum_{k=2}^{i} P(k|i) P(i)
\]

(21)

where the inner terms of the sum are given by Eq. (19) and Eq. (20) respectively. The corresponding saturation throughput is given by

\[
\eta_{BACK2F} = \frac{(1 - P_{\text{coll}}) T_d}{(1 - P_{\text{coll}}) T_S + P_{\text{coll}} T_C}
\]

(22)

Considering the structure of the BACK2F protocol, the values of \( T_S \) and \( T_C \) are equal to

\[
T_S = T_{\text{diffs}} + 2T_{\text{round}} + T_h + T_d + T_{\text{nifs}} + T_{\text{ack}} + 2T_p
\]

(23)

\[
T_C = T_{\text{diffs}} + 2T_{\text{round}} + T_h + T_d + T_p
\]

(24)

where \( T_{\text{round}} \) is the duration of a contention round in the frequency domain, reported in Tab. 1.

Finally, in RCFD there is no possibility of collisions and no idle slots. As a consequence, we have \( P_{tr} = 1 \) and \( P_S = P_{s,hd} + P_{s,fd} = 1 \), where

\[
P_{s,hd} = \frac{1}{N - 1}, \quad P_{s,fd} = \frac{1}{N - 1}
\]

(25)

The saturation throughput hence becomes

\[
\eta_{RCFD} = \frac{T_d P_{s,hd} + 2T_d P_{s,fd}}{T_S}
\]

(26)

where, in this case

\[
T_S = T_{\text{diffs}} + 3T_{\text{round}} + T_h + T_d + T_{\text{nifs}} + T_{\text{ack}} + 2T_p
\]

(27)

In this analysis we have considered the scanning time \( T_{\text{acc}} \) used in Eq. (3) equal to \( T_{\text{diffs}} \), to provide a fair comparison among all the MAC protocols.

### 3.3 Numerical results

In the previous subsection we have derived the saturation throughput for the different MAC protocols as a function of several system parameters. We will now numerically evaluate this metric for different network configurations and system parameters. Tab. 1 reports the simulation parameters in this evaluation, which are adopted from the IEEE 802.11 standard (b/g version) [24].

Fig. 4 shows the saturation throughput for all MAC algorithms versus the number of nodes in the network. The payload length has been kept fixed at 1000 Bytes, while the transmission rate is 1 Mbps, yielding a data transmission time of \( T_d = 8 \) ms.

It can be observed that the RCFD strategy outperforms all other MAC algorithms for any number of nodes. The two schemes that consider FD transmissions (RCFD and FD MAC) are able to provide a normalized throughput higher than one, for a small number of nodes. BACK2F and IEEE 802.11 RTS/CTS do not show a significant variation with the number of nodes, with the first one providing a higher throughput (close to 1) and performing close to RCFD for a large number of nodes. The standard IEEE
The standard IEEE 802.11 DCF without RTS/CTS, the first one always provides a higher throughput, thanks to its FD contention (RCFD and BACK2F) exhibit the same trend, even if significant impact. The techniques that include frequency–based represented by the exchange of RTS and CTS frames has a very poorly for short packets, since in that case the overhead strongly affected by the number of nodes, as expected.

Another evaluation is reported in Fig. 5 where we kept the number of nodes fixed at \( N = 10 \) and we varied the payload length, from 100 to 2300 Bytes. The transmission rate was kept fixed at 1 Mbps. Again, the proposed RCFD technique provides the best performance for all possible payload sizes. The techniques based on time domain RTS/CTS (IEEE 802.11 and FD MAC) perform very poorly for short packets, since in that case the overhead represented by the exchange of RTS and CTS frames has a very significant impact. The techniques that include frequency–based contention (RCFD and BACK2F) exhibit the same trend, even if the first one always provides a higher throughput, thanks to its FD capabilities. The standard IEEE 802.11 DCF without RTS/CTS, finally, yields the worst results, since it clearly suffers from the occurrence of collisions.

4 Simulation assessment

The theoretical results of Section 3 show a clear prevalence of the proposed RCFD algorithm over other MAC layer schemes considered. However, the analysis was conducted under some strong assumptions, the most important one being that all nodes are within the same collision domain. In order to relax this assumption, the five aforementioned MAC strategies have been compared through a network simulator developed in ns3, able to mimic the exchange of packets in a wireless network with multiple collision domains.  

4.1 Simulations setup

The standard distribution of ns3 already contains models for the IEEE 802.11 DCF, both with and without RTS/CTS, as defined in the standard. However, the modules for the MAC algorithms proposed in the literature, namely FD MAC, BACK2F and our proposal RCFD, were not available and therefore had to be purposely developed. Moreover, the standard ns3 wifi module only allows half–duplex communications, preventing a node from transmitting if it is receiving. In order to be able to simulate a network with full–duplex nodes, we adopted the patch discussed in [27], which allows to simulate an FD wireless network with ns3. It is worth stressing that, for the algorithms based on frequency domain operations (BACK2F and RCFD), the exchange of data over OFDM subcarriers is assumed to be ideal.

The simulated network is depicted in Fig. 6. It is an ad hoc wireless network composed of fixed nodes placed on a grid. The distance between two adjacent nodes in the same row or column is \( d \). The coverage range of each node includes all its one–hop neighbors and, within this area, the node can transmit and receive packets as well as overhear transmissions. To implement this channel model, the RangePropagationLossModel of ns3 has been adopted. The total number of nodes in the network is \( N = g^2 \), where \( g \) is the grid size and simulations have been conducted for several values of \( g \).

In each node, several applications are installed, one for each node within its coverage range, as shown in Fig. 6. The starting time of each application, \( t_i \), is distributed as an exponential random variable of parameter \( \lambda_i \). An OnOffApplication model is adopted where the duration of the ON and OFF periods are also exponentially distributed, with mean \( T_{ON} = T_{OFF} \). During the ON period, the applications generates constant bitrate (CBR) traffic with source rate \( G \). All packets have the same length \( L \) and the data rate at the physical layer, \( R \), is constant. It is noteworthy that

1. MATLAB simulations were reported in the conference version of this paper [1].
that the considered traffic model violates the assumption we made for RCFD, stated in Section 2.1, that all the nodes attempt to access the channel simultaneously. Consequently, to ensure that the RCFD protocol works properly even in this scenario, we have implemented a particular deferring policy, which will be described in Section 5.2.

Network operations have been simulated for a total of $T$ seconds (with the initial transient period removed), for different values of the grid size $g$ and different MAC algorithms. Given a certain parameter configuration, each simulation has been repeated a total of $N_s$ times and results have been averaged.

We considered two performance metrics, namely the normalized system throughput, $\Gamma$, and the average delay, $\Delta$. The normalized system throughput is the ratio of the total number of payload bits successfully delivered by all the nodes in the network over the simulation time $T$, and the offered traffic. We have

$$\Gamma = G \cdot N_a \cdot \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

where $N_a$ is the total number of running applications in the network, which is a function of the grid size $g$.

The average delay, on the other hand, is the arithmetic mean of the delay experienced by each packet in the network, defined as the time elapsed from the instant in which the packet is generated by the application to the instant in which the packet is successfully delivered.

Table 2 reports all the parameters adopted in the simulations.

It is worth noting that the simulation-based results are complementary with respect to those of the theoretical analysis presented in Section 3 since the analysis was based on the assumption of a single collision domain, whereas in the simulations we allow multiple collision domains.

### 4.2 Simulation results

In order to provide a comprehensive assessment of the presented protocol, in the network simulations we have evaluated its performance in two opposite scenarios:

I. **Long packet transmission time**: in this scenario large payload packets ($L = 1000$ Bytes) were exchanged at the lowest possible rate provided by IEEE 802.11b/g, namely $R = 1$ Mbit/s, resulting in a very long packet transmission time.

II. **Short packet transmission time**: in this scenario small payload packets ($L = 200$ Bytes) were exchanged at the highest possible rate, namely $R = 54$ Mbit/s, with a corresponding short packet transmission time.

In each scenario, the aforementioned performance metrics for the considered MAC algorithms have been evaluated for different values of the grid size parameter $g$, ranging from 3 (9 nodes) to 10 (100 nodes).

Fig. 7 shows the normalized system throughput $\Gamma$ for scenario I ($R = 1$ Mbit/s, $L = 1000$ Bytes).

Fig. 8 shows the normalized system throughput $\Gamma$ for scenario II ($R = 54$ Mbit/s, $L = 200$ Bytes).
opportunities. It is worth noticing that the normalized throughput values are considerably higher in Fig. 8 with respect to Fig. 7. Indeed, the higher PHY rate allows to exchange an increased amount of data in the same time.

As an interesting remark, which holds also for the other results presented in this section, it is worth noticing that the large majority of transmissions that took place in the simulated scenarios were HD transmissions. Indeed, the ON–OFF traffic pattern, combined with the FIFO policy adopted at each node’s queue, resulted in a low probability of establishing a bidirectional FD transmission. This is visible, for example, in the very small difference observable in Fig. 7 between the throughput curves for FD MAC and IEEE 802.11 with RTS/CTS, which are basically the same scheme with and without FD capability. Consequently, the more significant distance between RCFD and BACK2F is due not only to the first one being FD, but also to the ability of our protocol, which adopts a combination of time and frequency domain contention, to overcome the HT issues that, conversely, affect the BACK2F scheme.

The average delay Δ simulated in scenario II for all the MAC protocols is shown in Fig. 9. The strategies that include frequency domain channel contention once again outperform those based on a time domain approach, providing almost a 50% reduction in Δ. In particular, RCFD outperforms the BACK2F strategy also in terms of average delay, especially when a large number of nodes is considered. Similar results are achieved for scenario I, not reported here, where Δ is in general longer, due to the longer packet transmission time, and RCFD again outperforms all the other schemes.

Another significant advantage of the MAC protocols that include frequency domain channel access is their reduced variability in the packet delay with respect to the time–based strategies, due to the reduced randomness in channel access time. Indeed, time domain strategies based on the CSMA/CA algorithm are characterized by a considerable variability in channel access time, due to the random backoff procedure, whereas in frequency domain contention the time to access the channel is fixed, as expressed by Eq. (2) for the RCFD scheme. As an example, Fig. 10 reports the standard deviation of the delay for scenario II, which represents a significant metric to evaluate the variability of the channel access time. It can be observed that algorithms that take frequency domain contention into account outperform those based on a plain time domain approach and, in particular, RCFD exhibits the lowest variability, especially as the network size increases. The increased determinism of the RCFD protocol is of particular interest for applications with tight QoS requirements and, in particular, for industrial real–time applications.

As a final remark, it is worth recalling that a total of N s simulations for each MAC protocol and network size have been carried out. The 95% confidence intervals are reported in Table 3 for the case of average delay in scenario II (the confidence intervals for the system throughput and for the other scenario exhibit similar trends). It can be noticed that the variability of the results is low (and decreasing with the network size), thus ensuring that the curves presented in Figs. 7, 8, 9 and 10 accurately represent the algorithms’ behavior.

Table 3

| MAC Algorithm | N = 9 | N = 25 | N = 49 | N = 81 |
|---------------|------|-------|-------|-------|
| IEEE 802.11 DCF | 750.1 µs | 138.7 µs | 52.9 µs | 33.4 µs |
| IEEE 802.11 DCF RTS/CTS | 1164.7 µs | 417.6 µs | 280.9 µs | 44.8 µs |
| FD MAC | 1854.0 µs | 628.0 µs | 241.8 µs | 38.6 µs |
| BACK2F | 1288.1 µs | 363.4 µs | 177.6 µs | 99.9 µs |
| RCFD | 523.1 µs | 108.3 µs | 100.8 µs | 28.6 µs |

5 Protocol optimization and discussion

In this section, we discuss the assumptions on which the RCFD strategy is based and propose some possible enhancements.

5.1 Relation between available SCs and number of nodes
As mentioned in Section 2.1, the subcarrier mapping upon which the RCFD scheme relies imposes a limit on the number of nodes in the network, which has to be no higher than S/2.

It is worth stressing that the trend in wireless networks based on the IEEE 802.11 standard is to use wider channels, that offer an ever increasing number of SCs. As an example, IEEE 802.11ac introduces 80 MHz channels, that can accommodate 256 SCs and hence allow RCFD to reach up to 128 users.

The number of nodes can be further increased even maintaining a fixed number of SCs if we plan to exploit the information
Data on SC

For instance, if node \( n_1 \) in a system with \( S \) SCs be hosted in the network, and a 64-QAM modulation is employed, a total of 2048 users can be able to host multiple nodes within the same subcarriers. Each user can perform its transmission with the actual content of the symbol transmitted in a specific SC, to be able to host multiple nodes within the same subcarriers. Each SC can carry \( \log_2 m \) bits if an \( m \)-ary modulation is adopted and, in this way, the maximum number of users in the system can be increased to \( m \cdot S/2 \). As an example, if \( S = 64 \) SCs are available and a 64-QAM modulation is employed, a total of 2048 users can be hosted in the network.

Tab. 4 provides an example of extended subcarrier mapping in a system with \( S = 4 \) SCs which adopts a modulation of order \( m = 4 \), hence allowing the presence of 8 users. In this scenario, for instance, if node \( n_1 \) has to advertise a transmission to node \( n_6 \) in the second contention round, it would transmit bit 00 on SC \( s_1 \) (to advertise itself) and bit 01 on SC \( s_4 \) (to advertise the intended receiver).

### 5.2 Asynchronous channel access

An important assumption that was made in Section 2.1 is that the channel access is synchronous, i.e., all nodes try to access the channel at the same time. This is not realistic, since in real networks nodes often generate packets, and therefore try to access the channel, in an independent manner. As a consequence, when the proposed algorithm is implemented in a network with multiple collision domains, a node may start a contention procedure while another node within its range is receiving data, thus causing a collision. Indeed, the scanning procedure performed before the contention rounds is only capable of determining if a surrounding node is transmitting, not if it is receiving.

Fig. 11a reports an example of such a situation, where node \( n_3 \) tries to access the channel while node \( n_1 \) is already performing a data transmission to \( n_2 \), which is inside the coverage range of both nodes. When \( n_3 \) starts the first transmission round, it causes a collision with the ongoing transmission.

To cope with this issue, we make a simple yet effective modification to the algorithm presented in Section 2, so that an idle node (i.e., a node that does not have a packet to send), as \( n_3 \) in Fig. 11b, which hears a CTS from a neighboring node refrains from accessing the channel until the end of the transmission is advertised through an ACK packet. To prevent freezing (in case the ACK is lost), a timeout can be started upon CTS detection and the node can again access the channel after its expiration. Fig. 11b shows that, if such a deferring policy is adopted, no collision happens in the previously described scenario. We emphasize that the simulations of Section 4 were performed with the aforementioned deferring policy activated.

### 5.3 Impact of fading and collisions

In all the discussions so far we have assumed an ideal channel. Real wireless communication environments are characterized by impairments such as fading, shadowing and path loss. For our scheme, the case of selective fading, in which only narrow portions of the spectrum (corresponding to one or few subcarriers) are disturbed, is particularly challenging. Such a phenomenon could lead to sub-channel outage and the emergence of false negatives (FNs), i.e., missed detection of data on a subcarrier [22].

The impact of FNs in the three contention rounds of RCFD can be summarized as follows:

1) **First round:** Multiple PTs can be selected in the same collision domain as a result of FNs; as a consequence, nodes that should be RR in the second round would be PT instead and would not send the CTS in the third round, thus leading to missed transmission opportunities.

2) **Second round:** A FN during the second round could lead to a node not receiving an RTS destined to it, again resulting in a missed opportunity for a transmission which, however, should have been authorized.

3) **Third round:** Again, a FN occurrence during the third round results in a missed CTS reception and a corresponding missed transmission opportunity.

In conclusion, FNs induced by sub-channel outage never result in a collision but only in possible missed transmission opportunities, thus causing underutilization of the channel and slightly degrading the efficiency of the protocol.

Another possible issue arises when multiple nodes select the same SC in the first contention round, when the SC choice is random. This represents a problem in the BACK2F scheme [22], that was addressed by performing multiple rounds but still maintaining a residual collision probability, as reported in Section 5. Conversely, in our protocol, this could result in multiple PTs being present, only one of which is selected in the following rounds, thus preventing any possible collision.

### 5.4 Possible protocol improvements

The RCFD protocol in the presented form already yields significant performance benefits, as shown in Sections 5 and 4.

Further improvements in channel utilization can be achieved if the ACK procedure is also moved to the frequency domain, as already suggested in [23]. The implementation of this enhancement would be straightforward, since a mapping between nodes and subcarriers is already established.
Moreover, as discussed in [21] and [22], the random selection of OFDM subcarriers implicitly defines an order among the nodes trying to access the channel, thus enabling the possibility of fast and efficient TDMA–like transmissions. Alternatively, unlike we assumed throughout this paper, the order among nodes can be exploited if the nodes in the network have different priorities. In this case, the first round of the RCFD algorithm can be modified by letting a high priority node randomly choose its SC among a subset of $S$ which contains lower frequency SCs with respect to the set in which a low priority node picks its SC. This would guarantee to the former node a higher probability of being selected as a PT and, hence, a faster channel access.

6 Conclusions

The currently employed channel access schemes for wireless networks present several issues and relatively low performance. The introduction of full–duplex wireless communication can lead to increased performance, but also poses additional challenges to transmission scheduling and no standard MAC protocol has emerged so far as the best solution for FD wireless networks. In this paper we proposed RCFD, a full–duplex MAC protocol based on a time–frequency channel access procedure. We showed through theoretical analyses and network simulations that this strategy provides excellent performance in terms of both throughput and packet transmission delay, also in the case of dense networks, compared to other standard and state–of–the–art MAC layer schemes.

A natural extension of this work is the experimental validation of the proposed MAC layer protocol on devices capable of FD operations and able to transmit OFDM symbols using only some specific subcarriers. The suggested optimizations to the presented protocol could lead to even higher performance gains with respect to other MAC layer strategies.

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