# Cognitive Radio for Improved Reliability in a Real-Time Wireless MAC Protocol based on TDMA

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***Abstract*—Wireless communications enables introduction of Internet of Things (IoT) in industrial networks. Unfortunately, real-time guarantees required for many IoT applications, may be compromised in wireless networks due to an unreliable transmission medium. A key component in enabling real-time communications is the medium access control (MAC) layer and its ability to effectively avoid concurrent transmissions that causes deadline misses. Also, deploying the network in a harsh interference environment can lead to low reliability. Time diversity, based on transmitting several copies of the same data at different instants, increases reliability but at the expense of increased jitter and bandwidth. A more efficient resource utilization is expected from cognitive radio, which dynamically takes into account the status of the wireless environment before performing transmissions. This paper proposes a wireless MAC protocol based on scheduled timeslots to avoid concurrent transmissions, combined with two different mechanisms to increase reliability, one based on time diversity and another on cognitive radio. The protocol and its mechanisms to enhance reliability are compared in different interference scenarios, and show that cognitive radios achieves better performance than time diversity, especially when the interference is produced by a jammer.**

## I. Introduction

In industrial environments, networking between embedded systems relies mostly on the use of wired-based communication technologies. Yet, the application of wireless technologies is frequently considered a desirable option, due to advantages that include a reduced amount of wiring, ability to work in mobility scenarios, and easier network deployments. At the same time, a major trend in industrial networking is the adoption of the Internet of Things (IoT), based on the interconnection of an increasing number of devices with sensing and actuation capabilities. Such scenarios may require, e.g., a high density of devices as well as mobility, leaving wireless connectivity as the only feasible option. Unfortunately, wireless communications is more prone to suffer from interference and pathloss than wired communications, a factor that can compromise the quality of transmissions. This can be problematic for industrial settings, where a requirement to meet real-time deadlines is imposed by the need to respond to a physical world that develops dynamically with time.

An additional trend endeavours the convergence of communication technologies coming from the operational technology (OT) field (e.g. CAN and PROFIBUS), with focus on providing real-time communications; and technologies from the information technology (IT) field (e.g. IEEE 802.3 “Ethernet" and IEEE 802.11 “WiFi"), providing high throughput with affordable hardware [1]. In this context, Time-Triggered Ethernet (TTE) [2] is a wired communication technology based on standard Ethernet, able to provide real-time guarantees by applying the time-triggered communication paradigm, a time division multiple access (TDMA) protocol, where transmissions are performed at pre-defined points in time. With TTE, support to applications with heterogeneous communication requirements is enabled by means of three different types of traffic: time-triggered (TT), rate-constrained (RC) and best-effort (BE). TT is mainly designed for periodic traffic, while RC targets applications that require an average bandwidth not strictly periodic (e.g. audio and video streaming). Both TT and RC are real-time traffic, whereas BE performs as standard Ethernet traffic and does not provide any real-time guarantees. With TTE, the key to combine different traffic classes on a single switched Ethernet multi-hop topology is to schedule the real-time traffic, so that transmissions are deterministically assigned to happen at specific points in time [3].

A wireless extension to TTE can bring the support to applications with different traffic requirements to new operational fields requiring hybrid multi-hop wired-wireless networks. For example, wired TTE can act as the high throughput backbone in an industrial automation scenario, while the wireless extension can collect data from sensors and send orders to actuators that are not easily reachable with a wired connection. The extension can be built on IEEE 802.11 hardware, in a similar way as IEEE 802.3 and IEEE 802.11 work together. Low-energy and low-throughput solutions based on the well-known in industry standard IEEE 802.15.4 for wireless sensor networks (WSNs) are not suitable for applications in which high throughput is favoured instead of energy efficiency. Unfortunately, despite the high throughput capacity displayed by the physical layer of IEEE 802.11, the medium access control (MAC) layer based on carrier sense multiple access (CSMA) and the enhancements provided in IEEE 802.11e do not serve for the purpose of real-time [4].

The MAC layer plays a key role in communication systems by multiplexing the access to the transmission medium between several devices. When support to real-time communications is required, access must be provided within a bounded amount of time, so that transmissions can reach their destination before their deadlines expire. For this, the medium multiplexing needs to avoid that collisions between several devices occur, e.g., by scheduling the medium access in a TDMA fashion. However, even if collisions between devices are avoided, the problem of low reliability caused by other sources of interference remains to be solved. A common way to tackle the problem of low reliability is to use time diversity, in where several copies of the same data are transmitted at different points in time. Our previous work in [5] dealt with this idea, and showed that chances of successful delivery of data are increased, but at the expense of more bandwidth consumption and higher jitter. The cognitive radio (CR) technique is expected to overcome these limitations by adopting a more proactive approach [6]. CR monitors the wireless channels in the environment in an attempt to find an interference-free channel where transmissions can be sent more reliably.

This paper presents a MAC protocol suitable for wireless communications, compatible with TTE so that deadline guarantees to heterogeneous data traffic is given and enabling hybrid wired-wireless network support. The wireless MAC avoids concurrent transmissions between the wireless devices in the network, by using a TDMA protocol on top of the IEEE 802.11 MAC. The protocol includes a mechanism for increased reliability based on time diversity from [5], and a new one based on CR. A scheduler is presented, that enables hybrid wired-wireless multi-hop support, and handles TT and RC traffic taking into account the requirements of the time diversity and CR based mechanisms. To evaluate the performance, a simulation in OMNeT++ [7] has been developed, and results are compared for different combinations of reliability mechanisms and interference.

The rest of the paper is structured as follows. Section II presents some background and reviews related work dealing with improved reliability at the MAC level. Section III describes the proposed MAC protocol and the applied reliability mechanisms. Section IV presents the simulation developed to evaluate the protocol and the acquired results. Finally, Section V concludes the paper.

## II. Background and Related Work

Even if access to the wireless medium is provided with a bounded latency, the problem of low reliability can still compromise the success of the transmissions. The main reasons include fading, pathloss and the presence of interference. Interference can be especially harmful in industrial deployments, where a harsh environment full of machinery and electrical components exist. Interference can also be present to a great extent in the industrial, scientific and medical (ISM) radio bands used by IEEE 802.11 and IEEE 802.15.4, where access to the medium is free and an unbounded amount of devices can try to transmit simultaneously. Moreover, it has been shown that adjacent channels in IEEE 802.11 and IEEE 802.15.4 also interfere [8] [9]. Thus, in general it cannot be guaranteed that the environment will be free of interference.

To overcome this issue, time diversity mechanisms can be used, but are limited by the real-time deadlines of the traffic, that do not allow an unrestricted number of transmissions, and by the high jitter associated with the dissimilar moments when a transmission succeeds. In [10], a characterization of the interference level in IEEE 802.11 networks for industrial channels concludes that message delivery is generally achieved with at most two transmissions, and that small messages require fewer number of transmissions. The IEEE 802.11 standard has support for time diversity, but the number of transmissions is not deterministic and can take a random amount of time [11]. It is therefore not surprising to find literature that focuses on how to provision additional transmissions while at the same time considering real-time deadlines. In [12] and [13], a real-time schedulability analysis is made, that considers time diversity to battle against interference. Further, [13] allows to reuse scheduled transmissions that are no longer needed. In [14] and [15], the number of required transmissions to achieve a particular reliability level is calculated based on probability of message delivery for a given channel model. Unfortunately, the scheduling solutions presented in [12]-[15] are only valid for wireless networks, and do not consider the operation in multi-hop mixed wired-wireless scenarios.

The CR approach, on the contrary, does not try to perform additional transmissions, but to maximize the probability of a successful delivery for every single transmission. CR is based on a radio procedure that allows a device to monitor the wireless channels in the environment and adapt to them. A CR-based system can take decisions based on environment information, and reconfigure the parameters of a software defined radio (SDR), a radio where the signal processing components are implemented by means of software or programmable logic devices. Although CR was first thought to transmit on the underused channels in licensed bands, it has been proposed to improve reliability by avoiding interference also in ISM bands [16] where no primary licensed user is present. Several CR-based solutions have been presented to cope with interference in ISM bands for real-time systems. In [17] CH-MAC uses a common control channel (CCC) to share control information and take decisions on which channel to use. A similar proposal has been done in [18], but in this case the devices have two antennas. One of the antennas operates in a dedicated CCC and the other is used to transmit data and is dynamically reconfigurable. However, both MAC protocols are based on a CSMA method, so no bounded access time is provided. A TDMA approach for the CCC is used in [19], where control data is transmitted to an access point (AP) that performs a decision. However, all these MAC schemes depend on a CCC, which may be of low quality due to interference, making it impossible to exchange control information. As a result, some other designs which do not depend on a CCC have been proposed. This is the case of [20], where a specific period is reserved to share coordination data between the devices. The time frame is divided into 4 different periods: sense, control, feedback and data. All devices get information about the environment during the sensing time. Then, this information is sent to an AP which analyses it. Afterwards, the AP sends the taken decision in the feedback period, and finally, devices access the medium according to a TDMA method to transmit data. A rendezvous process may be used to tune to the same channel. In the rendezvous process, devices look for each other in the available channels, i.e., a device tries every channel until it comes across the destination device. In [21], a rendezvous sequence has been designed in order to ensure that two devices come across each other in at least one channel over the sequence duration. Therefore, if there is an available channel between the sender and the receiver, this MAC ensures correct reception. In [22], some of these CR proposals have been evaluated in industrial environments and compared with non-CR-based MAC schemes, proving that CR can be used to cope with interference in these environments.

To the best of our knowledge, the described CR-based MAC protocols have not been adapted to operate in the context of a multi-hop wired-wireless networks with support to traffic with different timing requirements.

## III. MAC Protocol for Improved Reliability

### A. Network and traffic model

The network model comprises two types of devices: end-systems (ES) and switches (SW). The topology of the network allows ESs and SWs to be connected with point-to-point links. The ESs are the source and destination of traffic, and a direct connection between them is not possible, so that any transmission must go through the SWs. This results in star topologies, where every ES is directly connected to a SW. Two SWs can also be connected through a point-to-point link, allowing the star network to be part of other star networks, in a topology design called snowflake. The links can either be wired or wireless. SWs having a wireless interface are called AP, whereas the ESs are called wireless ESs (WESs). The topology of the multi-hop network is modelled with an undirected graph $G(V, E)$, where $V$ are the vertexes (devices), and $E$ the edges (physical links). Every physical link is bi-directional, comprising a pair of dataflow links. The set of all dataflow links $L$ is defined as follows

$$\forall v_1, v_2 \in V : (v_1, v_2) \in E \Rightarrow [v_1, v_2], [v_2, v_1] \in L, \tag{1}$$

where $(v_1, v_2)$ defines an undirected edge (physical link) and $[v_1, v_2]$ describes a directed edge (dataflow link). Every dataflow link defines a collision domain. A collision domain is a section of the network in where messages sent by two or more devices can collide. In the case of wireless links, it is assumed that they are all in range of each other and define a single collision domain (Figure 1).

The traffic model for the network considers the three traffic classes of TTE. Given a message $m$, the characterization of the traffic is as follows. TT is periodic traffic, therefore defined by a period $m.t_{period}$. RC is characterized by an average bandwidth, expressed in the form of a minimum interarrival time between two consecutive messages $m.t_{MIA}$. All traffic classes, TT, RC, and BE are also characterized by their data length $m.d_{length}$. For simplicity, RC traffic can be modelled as TT, given that in the worst case a RC message will be generated every $m.t_{MIA}$, making it periodic with period $m.t_{period} = m.t_{MIA}$.

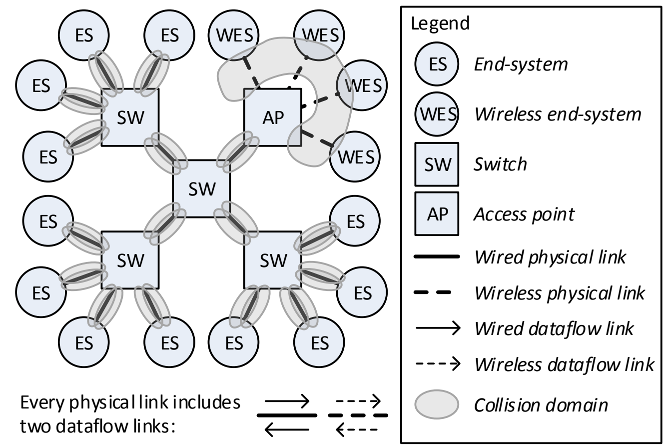


Fig. 1. Example of hybrid wired-wireless multi-hop network with snowflake topology.

### B. Time diversity operation

To characterize the time diversity mechanism for a TT or RC message, two parameters were considered in [5]: the number of times $m$ is transmitted $m.n_{transm}$ and the time difference between two consecutive transmissions of the same message, named inter transmission interval $t_{ITI}$. Given that the reliability can vary significantly between links, $m.n_{transm}$ is redefined in this paper to be expressed per link, so that it now refers to the number of times $n_{transm}$ a message $m$ is transmitted on link $[v_i, v_j]$: $m^{[v_i,v_j]}.n_{transm}$. This allows, e.g., to increase the number of transmissions for a message on those links that are less reliable (e.g., wireless links). Both $m^{[v_i,v_j]}.n_{transm}$ and $t_{ITI}$ can be tuned to combat interference. Specifically, our previous paper [5] considered the adaptation of $t_{ITI}$ to the interference burst size and $m^{[v_i,v_j]}.n_{transm}$ to the level of interference so that the desired reliability level is achieved. As a consequence, two diversity schemes were proposed that play with the value of $t_{ITI}$: Consecutive time diversity scheme and Spread time diversity scheme. In the Consecutive scheme, the transmission attempts are placed one after another, whereas in the Spread scheme, these are placed as far apart as the deadline allows in an attempt to avoid bursts of interference.

Further, our previous work included the use of feedback mechanisms that acknowledge the reception of a transmission. The feedback mechanism is used to inform when an additionally scheduled transmission is no longer needed, in which case BE traffic may take advantage of the remaining time. Further details about this mechanism are out of the scope of this paper, but can be found in [5].

### C. Cognitive radio operation

In order to support CR capabilities in the wireless MAC protocol, CR phases have to be added periodically (Figure 2). A similar approach to [20] is used, which has been evaluated in different industrial environments in [22]. CR phases are characterized by a duration $t_{length\_CR}$, and the period at which they appear $t_{period\_CR}$. These periodic phases are divided into spectrum sensing (SS) phases and CR control (CC) phases. During the SS phases, the devices carry out SS tasks to gather environmental information. In this case, the SS algorithm allows the devices to know whether a channel is free or interfered by an external user. As the goal within each AP domain is to find a common channel to use which is the least compromised by external interference, the SS task is carried out by all the devices in the network at the same time. Each device senses a different channel, which is assigned to them during the SS by the scheduler. In this way, as many channels as devices are in the network can be sensed during a cognitive phase. Further, the channel which a device senses changes from one cognitive phase to the next, allowing the network to maximize the spatial diversity of all devices for spectrum sensing. Once the sensing results are obtained, all devices send their information to their AP within the CC phase.

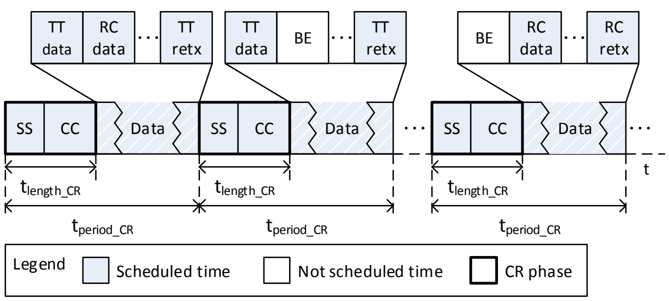


Fig. 2. CR phases allocation in the MAC. An example for the data allocation is also provided.

Once the SS results are transmitted to the AP, it uses them to obtain statistics about the external interference of all the channels. To do so, a Markov Process [23] is used, that estimates the probability of availability of each channel. Then, the AP creates a joint list of channels organized according to their availability estimated by the Markov Process, that is sent to all the devices in the AP coverage area. Next, each device synchronizes its radio to the first channel in the joint list. By using this scheme, the system chooses the less interfered channel. However, an external interference could potentially jam the channel used by the network to exchange information during the cognitive phase, making the exchange of CR data impossible. To solve this problem, all the devices in the networks check if the others sent their results during the CR phase, and in case no results from any other devices are received, the channel is considered as interfered. In this situation, the network uses the list sent in the previous cognitive phase to hop to the second channel in the list and carry on its operation.

The CR phases add to the system the capability of avoiding interference; thus, the system is more robust in interfered environments. However, this robustness is not for free, these phases lead to a protocol overhead in terms of higher energy consumption or lower throughput. Due to the fact that the system cannot transmit during these phases the throughput is reduced. In the same way, these phases prevent the system from going into an idle state with lower energy consumption.

### D. Scheduling

With TTE, the transmission of real-time traffic is handled by a schedule that specifies the instants in time when a message should be dispatched from the point at which it is generated, and through every hop, towards the final destination. The remaining time after the allocation of TT and RC traffic can be utilized by BE traffic, given that it does not have any guarantee of delivery. Every real-time message $m$ is decomposed in a set of message instances $m^{[v_i,v_j]}$, corresponding to a transmission on every dataflow link $[v_i, v_j]$ from the set of dataflow links $L$ that the message needs to cross to be transmitted from the sender to the receiver. A message instance is characterized by $m^{[v_i,v_j]} = \{m.t_{period}, m.d_{length}, m^{[v_i,v_j]}.n_{transm}, m^{[v_i,v_j]}.t_{offset}\}$, where $m^{[v_i,v_j]}.t_{offset}$ represents the instant when a message instance needs to be transmitted, formulated as the offset from the moment when the schedule begins. The task of calculating $m^{[v_i,v_j]}.t_{offset}$ is performed by the scheduler. The calculation is based on the use of first-order logic constraints, which is a powerful mathematical tool that enables the modelling of the network topology and its traffic with simple mathematical expressions that can be combined in a scalable way. In this paper, the focus is on the constraints that avoid that two messages are scheduled to be sent on the same dataflow link at the same time, referred as *avoid-collision* constraints.

Since some of the dataflow links are wireless, it is not enough that concurrent transmissions in one dataflow link are avoided, given that the wireless medium typically is half-duplex and parallel transmissions on different dataflow links that are in range of each other therefore define a collision domain. A solution to the modelling of half-duplex transmissions was already made in our previous paper [5], but we revisit it here partly for clarity and partly to extend it to support dataflow links with different transmission speeds. First, $L$ is redefined, so that a distinction between wired dataflow links $L_{wd}$, and wireless dataflow links $L_{wl}$ is made and $L = L_{wd} \cup L_{wl}$. Further, it is necessary to consider that different transmission media can translate to different data rates $R$. This implies that the transmission time depends on the medium where the message instance is transmitted, and is given by $m^{[v_i,v_j]}.t_{transm} = m.d_{length}/R^{[v_i,v_j]}$, where $R^{[v_i,v_j]}$ is the transmission rate on dataflow link $[v_i, v_j]$.

Given that $M$ is representing the set of all messages, and $LCM(M.t_{period})$ is referring to the least common multiple of all message periods assuming that the periods are harmonic, the following equation formulates the avoid-collision constraints for wireless dataflow links and time diversity that enables dataflow links with different transmission speeds:

$$
\begin{aligned}
&\forall [v_k, v_l], [v_q, v_r] \in L, \forall m_i, m_j \in M,\\
&\forall a \in \left\{0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_i.t_{period}} - 1\right)\right\},\\
&\forall b \in \left\{0, 1, ..., \left(\frac{LCM(M.t_{period})}{m_j.t_{period}} - 1\right)\right\},\\
&\forall c \in \{0, 1, ..., m_i^{[v_k,v_l]}.n_{transm} - 1\},\\
&\forall d \in \{0, 1, ..., m_j^{[v_q,v_r]}.n_{transm} - 1\}:\\
&((m_i \neq m_j) \wedge \exists m_i^{[v_k,v_l]} \wedge \exists m_j^{[v_q,v_r]}\\
&\wedge ([v_k, v_l] \in L_{wl} \wedge [v_q, v_r] \in L_{wl})) \Rightarrow\\
&((a \times m_i.t_{period}) + m_i^{[v_k,v_l]}.t_{offset} \geq\\
&(b \times m_j.t_{period}) + m_j^{[v_q,v_r]}.t_{offset}+\\
&m_j.d_{length}/R^{[v_k,v_l]} + d \times t_{ITI})\\
&\vee\\
&((b \times m_j.t_{period}) + m_j^{[v_q,v_r]}.t_{offset} \geq\\
&(a \times m_i.t_{period}) + m_i^{[v_k,v_l]}.t_{offset}+\\
&m_i.d_{length}/R^{[v_q,v_r]} + c \times t_{ITI}).
\end{aligned}
\tag{2}
$$

The constraints defined in Equation 2 can be used in addition to the avoid-collision constraints defined in [3] for the wired segment, so that a schedule for a hybrid wired-wireless network is obtained. Equation 2 can also be used to account for the CR phases. These phases can be modelled in the form of avoid-collision constraints, given that during the CR phases, no traffic can be sent on the wireless links. The CR phases are characterized by a duration $t_{length\_CR}$, and the period at which they appear $t_{period\_CR}$, so they can be modelled in the same way as TT/RC and be included in $M$, provided that the duration is fixed to $t_{length\_CR}$ instead of being dependant on $m.d_{length}/R^{[v_i,v_j]}$, and $m^{[v_i,v_j]}.n_{transm}$ is set to 0.

A solution that satisfies the given constraints can be obtained by using satisfiability modulo theories (SMT) solvers [3].

Further, with TDMA protocols, a common notion of time for all the devices is required, so that the instants when the messages need to be transmitted are consistent and collisions are avoided. A common notion of time is generally achieved by using synchronization protocols, that are based on the periodic exchange of timestamps. These timestamps are combined in a central device that sends out a new calculation of time that is used by the rest of devices to adjust their clocks. This exchange can be handled by mapping the messages to the TT class.

## IV. Simulation and Results

### A. Simulation setup

In order to evaluate the proposed system, a model in the OMNeT++ discrete event simulation framework has been created with support of the INET library. The MAC works on top of the 802.11b physical layer, supported in the INET version used for this simulation, but the results focus on comparing different configurations and are also valid for the up-to-date version of the standard IEEE 802.11-2012. The simulation model was originally presented in [5], and in this paper CR has been added to perform a comparison between time diversity and CR. The model allows choosing between time diversity or CR to increase reliability, and also both or none of the mechanisms may be used at the same time. For time diversity, the Consecutive and Spread schemes have been implemented in the simulator with the maximum number of retransmissions set to 1 ($n_{transm} = 2$). This value shortens the simulation time, while still showing the necessary performance differences. In the CR-based MAC case, the system hops according to the spectrum sensing results among 5 different channels, as does the frequency hopping (FH)-based interference. The simulated reliability configurations are summarized in Table I.

In the evaluation, the percentage of failed messages and the average MAC to MAC delay have been measured. The percentage of failed messages provides an evaluation of the performance of the schedule for real-time traffic. A message is tagged as failed when all the scheduled transmissions for this message are unsuccessful. Note that no retransmission can be scheduled after the message deadline. The MAC to MAC delay, which is only measured for successful messages, i.e., messages that arrive before the deadline, is measured as the time from the moment when a message is transmitted for the first time until it is successfully received, which can happen at the first attempt or later. Consequently, it measures the delay introduced by the time diversity schemes, that grows with every transmission attempt.

A wireless network composed of five WESs and one AP has been used in the simulator to evaluate the proposed MAC protocols as shown in Figure 3. An additive white Gaussian noise (AWGN) channel has been considered to evaluate the proposed MAC. The focus of the paper is on increasing the reliability of the wireless MAC protocol. For that reason, the wired segment has not been simulated. TT and RC messages with a size of $d_{length} = 62$ bytes (4 of them are payload) are generated in the WESs and sent to other WESs through the AP. In each simulation, at least 5000 messages are transmitted. The parameters of the simulated system are shown in Table II. The network is installed in an environment with interference, and two types of interference have been taken into account: intelligent interference that do not attempt to interrupt an ongoing transmission such as CSMA to represent IEEE 802.11 or IEEE 802.15.4 users, and jamming interference, as provoked by electromagnetic interference due to industrial equipments. Two different interference level have been simulated (10% and 30% of the total time), transmitted in bursts of different sizes (1, 15 or 30 times the length of a message). The latter is used to set the value of $t_{ITI}$ for the scheduler. Further, both FH-based interference and static interference have been considered. The former models, e.g., Bluetooth systems, while the latter is used by IEEE 802.11 transmissions. The worst interference scenario is represented by jamming 30% of the time, an extreme situation, i.e., not many protocols cope with this high level of interference. Table III shows a summary of the parameters of the simulated interference.

TABLE I
SIMULATED RELIABILITY CONFIGURATIONS.

| Setup | Cognitive radio | Time diversity |
|---|---|---|
| Setup 1 | Not used | Not used (0 retransmissions) |
| Setup 2 | Not used | Consecutive scheme (1 retr.) |
| Setup 3 | Not used | Spread scheme (1 retr.) |
| Setup 4 | Used | Not used (0 retr.) |
| Setup 5 | Used | Consecutive scheme (1 retr.) |
| Setup 6 | Used | Spread scheme (1 retr.) |

TABLE II
SIMULATED SYSTEM PARAMETERS.

| Parameter | Value |
|---|---|
| Message length | 62 bytes |
| Number of messages transmitted | $\geq$ 5000 messages |
| Data rate | 11 Mbps |
| Slot duration | 240 $\mu s$ |
| CR phase duration | 2.4 $ms$ |
| CR phase period | 240 $ms$ |

TABLE III
PARAMETERS OF THE SIMULATED INTERFERENCE.

| Name | Value |
|---|---|
| Type of interference | CSMA<br>Jamming |
| Level of interference | 10%<br>30% |
| Interference burst size (as multiple of the size of data messages) | 1<br>15<br>30 |
| Frequency hopping (FH) | Yes<br>No |

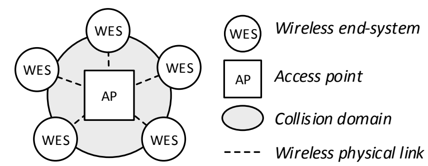


Fig. 3. Simulation scenario.

### B. Simulation results

In Figure 4, the percentage of failed messages is shown for both the CR-based and the non-CR-based MACs without time-diversity. In the non-CR-based MAC case, results are shown for both FH-based interference and static interference. However, no results are shown for static interference in the CR-based MAC case because for this environments the failed messages are 0, given that the system hops to a non-jammed channel once the interference is detected. Results are provided with colored bars for CSMA interference with different loads and burst sizes, while the thinner bars represent the same performance parameter but for the jamming interference. It can be seen from these results how jamming interference leads to a higher number of failed messages than CSMA, given that CSMA devices backoff if the medium is busy. The results also show a lower number of failed messages for the CR-based MAC. Therefore, the proposed CR scheme adds robustness to the system in interfered environments by reducing the number of errors. Failed transmissions have been reduced from more than 50% in the jamming interference (or 30% in the CSMA case) to less than 10% for every evaluated interference. For this comparison the worst case has been considered, which is the static interference for the non-CR-based MAC and the FH-based interference for the CR-based MAC. Regarding the load and the burst size of the interference, the non-CR-based and the CR-based MACs have different behaviour. For the non-CR-based MAC, the lower the burst size is, the higher the error rate. This is because a lower burst size also means a more frequent interval for the same level of interference, thus, it provokes a higher number of errors. On the other hand, in the CR-based MAC case, the lowest error rate is obtained for the larger burst size. The reason is that a less frequent interference interval makes the CR-based MAC to suppose the channel is free, with higher probability of collision than for more frequent interference intervals.

The percentage of failed messages with Consecutive and Spread schemes are shown in Figure 5 and Figure 6, respectively. Regarding the non-CR-based MAC, it can be seen by comparing both figures that the Consecutive scheme is a better policy for CSMA interference, while the Spread scheme is better for jamming interference, as already concluded in [5]. Any of these two policies can cope with CSMA interference, and the error rate has been reduced to 0.05% when using the Consecutive scheme and to 3.5% when the Spread scheme is used. Nevertheless, the jamming interference is still quite harmful for both the Consecutive and the Spread scheme. It is in this case that the CR approach is useful, because the CR-based MAC achieves better results without time diversity (Figure 4) than the non-CR-based MAC with time diversity. Therefore, CR achieves better results than time diversity in these kinds of environments. Moreover, even better results are obtained if time diversity is added to the CR-based MAC (the rightmost bars in Figure 5 and Figure 6). In this case, errors have been reduced to 0% for CSMA interference and to 4% for jamming interference using the Spread policy.

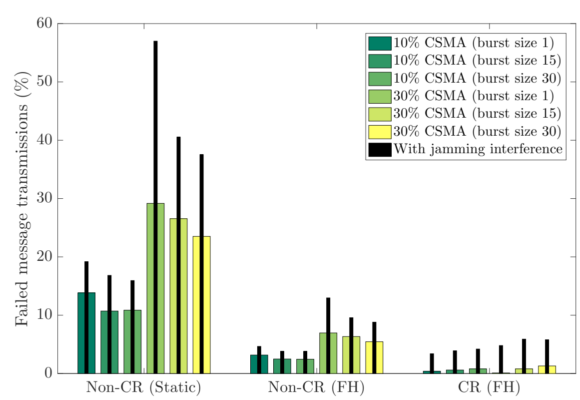


Fig. 4. Percentage of failed messages for non-CR and CR-based MAC without time diversity.

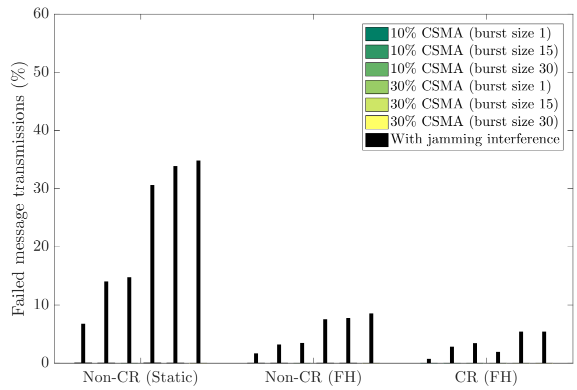


Fig. 5. Percentage of failed messages for non-CR and CR-based MAC following the Consecutive time diversity scheme.

The average MAC to MAC delay has been measured for all the configurations described above. Figure 7 and Figure 8 show the delay using the Consecutive and Spread schemes respectively. When time diversity is not used, the delay is always the same for all considered MACs because every message is transmitted only once and discarded if it fails. Hence, no results from this are shown. Average delays are represented for different load and burst lengths of a CSMA interference, and the same parameter is shown by thinner bars for the jamming interference. Also, the minimum and the maximum delay are shown in both figures in red dash lines. The minimum and maximum delays correspond to the time achieved when the message is not retransmitted and when it is retransmitted once, respectively. Results for the non-CR-based MAC are shown for static interference and FH-based interference, whereas results for the CR-based MAC are only shown for the FH-based interference. This is due to the same reason as above, the CR-MAC hops to a free channel and results are the same as if the channel is not jammed. Under the Consecutive policy, the delay does not grow considerably in any of the considered cases. However, in the Spread case, the delay and especially the variance of the delay is much larger, since the additional transmission slots are more spaced. The delay is lower in the CR-based MAC because a lower number of retransmissions needs to be used due to its capability to avoid interference.

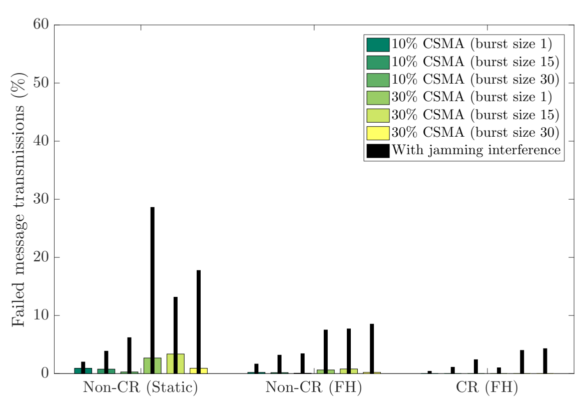


Fig. 6. Percentage of failed messages for non-CR and CR-based MAC following the Spread time diversity scheme.

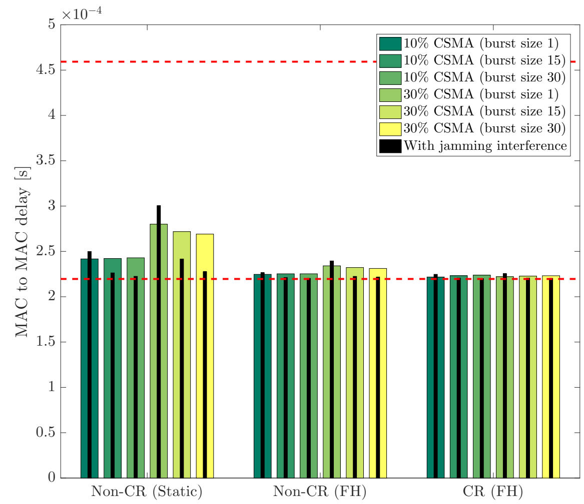


Fig. 7. Average MAC to MAC delay for non-CR and CR-based MAC following the Consecutive time diversity scheme.

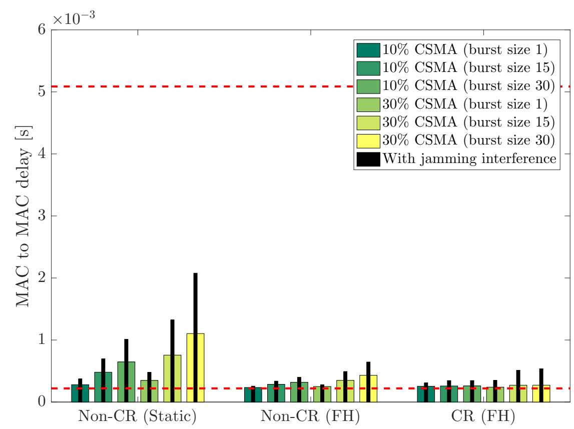


Fig. 8. Average MAC to MAC delay for non-CR and CR-based MAC following the Spread time diversity scheme.

With regards to the jitter, it only occurs with the time diversity scheme. Jitter of $240\mu s$ and $4.9ms$ have been obtained for the Consecutive and Spread schemes respectively. While the jitter is 0 when no time diversity is considered.

Taking into account both failed messages and average delay, the CR-based MAC with no time diversity achieves lower fails than the non-CR-based MAC with time diversity, and it does not lead to an increase in the delay or jitter. This is a desired goal for real-time communications which demand high requirements in terms of delay and jitter. If the applications requires a higher reduction of the failed messages, CR and time diversity may be used jointly, but at the cost of increasing the average delay.

## V. Conclusion

In this paper, two techniques are proposed and compared for increased reliability in a wireless TDMA MAC protocol: one based on time diversity and another on spectrum planning using cognitive radios. For time diversity, two policies on how to schedule retransmissions have been implemented: Consecutive and Spread. To add CR to the MAC, periodic phases have been scheduled in the TDMA scheme to decide which channel to use, based on the one that is expected to be more reliable for transmissions. Both mechanisms have been evaluated in environments, subject to interference of different type, duration and persistence. The evaluation includes percentage of failed messages and average MAC to MAC delays. The results show that a scheme using CR achieves better results than one using time diversity in all the considered environments, since the CR scheme is able to reduce the percentage of failed messages more than the time diversity scheme. The percentage of failed messages has been reduced to less than 10% using CR, while percentages higher than 30% have been obtained for some interference when time diversity is used. Furthermore, this reduction does not come at the expense of an increase in the average MAC to MAC delay, as in the case of time diversity. On the other hand, CR leads to some disadvantages as lower energy efficiency or lower throughput. In addition, a scheme using both time diversity and CR have been evaluated, obtaining an even higher reduction in the number of failed messages. Percentages of failed messages lower then 4% have been obtained when both techniques are used at the same time. However, an increase in the average MAC to MAC delay should be considered in this case as the scheme includes retransmissions.

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