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A LOW COORDINATION OVERHEAD C-ARQ PROTOCOL WITH FRAME COMBINING

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ABSTRACT

This paper proposes a low coordination overhead cooperative Automatic Repeat reQuest (ARQ) scheme with an integrated frame combiner, which exploits space diversity and cooperation between neighbouring nodes. In channels with a strong Line of Sight (LOS) component and low Signal-to-Noise ratio (SNR), the maximum achievable throughput of the proposed protocol is many times higher than for other ARQ schemes. For non LOS scenarios, the cooperative ARQ without frame combiner achieves the best efficiency results, and the overhead introduced by the frame combiner mechanisms leads to results which can be even below the classical ARQ mechanism.

I. INTRODUCTION

Cooperative protocols for wireless communication networks are gaining greater interest among the research community [1]. The main idea behind this novel approach to wireless networking is to exploit the broadcast advantage and spatial diversity of wireless transmission. An important example of cooperative protocol is the recently proposed *Cooperative-ARQ* (*C-ARQ*), which is a variant of the well-known ARQ (Automatic Repeat reQuest) protocol; see [3],[4],[5],[6],[7].

The basic operation of C-ARQ can be described as follows: Assume a node x must transmit a frame to a node y. Nodes x and y could be, for instance, two nodes of an ad-hoc or mesh network, or an access point and a mobile terminal of an infrastructured WLAN. Assume also that node y has designated *M-1* nearby nodes as *cooperator nodes*. When x transmits the frame addressed to y, the cooperators of y will also receive a copy of the frame. As in any ARQ protocol, if node y receives the frame with erroneous bits, it will ask for a frame retransmission. In C-ARQ, however, the node y will first request a retransmission to their cooperators: if a cooperator node has received the frame correctly, it will perform the retransmission instead of x. Recall that cooperator nodes are nearby y, and it is very likely that this retransmission will be received correctly by y. In case no cooperator node has the correct copy of the frame, y will request a retransmission from x.

The paper focuses on a variant of the basic operation of C-ARQ, called *C-ARQ with Frame Combiner* (*C-ARQ/FC*). In this variant of C-ARQ, even when no cooperator node has a correct copy of the frame, the cooperators send their incorrect frames to y that, using this information, tries to reconstruct the original frame. The frame reconstruction is performed by means of a so-called frame-combiner (FC). Only if the frame reconstruction is unsuccessful, y will request a retransmission from x.

As we will show, both C-ARQ and C-ARQ/FC lead to a considerably low *equivalent Frame Error Rate* (FER), defined as the probability that a frame requires a retransmission from node x. Both mechanisms, however, introduce an extra coordination overhead, due to the required node-to-cooperators and cooperators-to-node communication. This is exacerbated in the latter case, as the cooperator nodes must send copies of erroneous frames to y. Decreasing the equivalent FER and increasing the coordination overhead have opposite effects on the efficiency of the protocol. It is thus necessary to study under which conditions these techniques lead to practical benefits.

The main contributions of the paper are the following:

(i) A novel frame exchange mechanism between a node and its cooperators for C-ARQ/FC. This exchange method exploits the strong correlation between erroneous frames received by different nodes in order to compress the information exchange, thus reducing considerably the coordination overhead.

(ii) A performance evaluation of equivalent FER and maximum achievable throughput for C-ARQ and C-ARQ/FC in Ricean channels, having as particular cases the Additive White Gaussian Noise (AWGN) and the Rayleigh channels. In AWGN, we can obtain for both mechanisms an analytical expression for equivalent FER. For other channels we have used simulation. Simple formulas for the maximum achievable throughput for both mechanisms and any channel are also derived.

Our main findings are the following:

(i) Both C-ARQ and C-ARQ/FC reduce considerably the equivalent FER compared with the classical ARQ for all the studied scenarios. In channels with a strong Line-of-sight (LOS) component, the equivalent FER for C-ARQ/FC can be several orders of magnitude lower than for C-ARQ. This difference in equivalent FER values is considerably less in the case of NLOS scenarios.

(ii) In channels with a strong LOS component and low Signal-to-Noise ratio (SNR), the maximum achievable throughput of C-ARQ/FC is much higher than for C-ARQ and classic ARQ. The difference reduces when the LOS component becomes weaker, when C-ARQ becomes the best option. In Rayleigh channels, for instance, C-ARQ and even classic ARQ achieve a higher efficiency than C-ARQ/FC.

The combined use of C-ARQ and a FC was first proposed in [7]. In this work, however, the coordination overhead was not addressed, and no frame exchange mechanism was proposed. The analysis was focused on determining asymptotic BER expressions and comparing them with the Maximal Rate Combining receiver diversity technique.

The idea of adding incremental information to an erroneous packet copy has been studied by many authors. The

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basic principle behind these schemes is that the received copies of a packet should not be discarded by the receiver node even if they have errors, as they contain useful information about the correct copy of the frame; see [8],[9],[10],[11]. These schemes are, however, non cooperative, in the sense that the additional information is added always by the original transmitter.

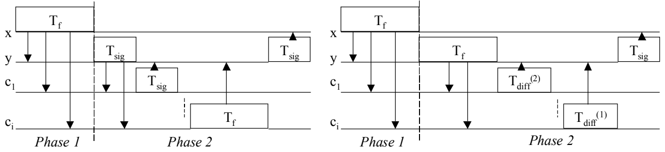
The paper is organized as follows: Section II describes the C-ARQ/FC variant proposed in this paper and discusses the coordination overhead of both C-ARQ and C-ARQ/FC. Section III studies the FER under different channel conditions, presenting some numerical examples. Section IV presents an efficiency study for both systems. Finally Section V is devoted to conclusions.

II. A LOW COORDINATION OVERHEAD C-ARQ/FC

In this section we propose a low coordination overhead C-ARQ/FC protocol. We motivate the proposed protocol, by first examining the coordination overheads of C-ARQ.

A. Overhead of C-ARQ

The C-ARQ protocol operates into two phases; see Fig. 1.a. *Phase 1* starts when node *x* sends a frame to node *y*. If the frame is correctly received by *y*, node *y* will send back a short signalling message with an acknowledgement, and provided that this short message is received correctly by *x*, the frame transmission process will be finished. If *y* receives an erroneous copy of the frame sent by *x*, *Phase 2* of the protocol starts: Node *y* will broadcast a short signalling message asking their cooperators for a correct copy of the frame. The cooperator nodes start a round robin in which they send either (i) a short signalling message indicating that they do not have a correct copy of the frame, or (ii) a message with the copy of the received frame, if they have received the frame correctly. In the latter case, the round robin is stopped after the correct frame is sent to *y*.



(a) C-ARQ (b) C-ARQ/FC

Figure 1: C-ARQ and C-ARQ/FC operation. We show the case in which cooperator c_i is the first to have the correct copy of the frame.

Phase 2 will have different average durations depending on two possible conditions: (i) If no cooperator has a correct copy of the packet, the duration of Phase 2 is given by $A_{Ph2}^{(1)} = (M+1) \times T_{sig}$, where T_{sig} is the transmission time of the signalling messages. (ii) otherwise, the average duration of Phase 2 is $A_{Ph2}^{(2)} = T_f + \left(\frac{M}{2}+1\right) \times T_{sig}$, where T_f is the transmission time of a data frame.

B. The proposed low coordination overhead C-ARQ/FC

In C-ARQ/FC protocol, even when any cooperator node has a correct copy of the frame, the cooperators send their incorrect frames to *y* that, using this information, tries to reconstruct the original frame. A direct implementation would lead, however, to a too high coordination overhead. In order to reduce the signalling overhead, we exploit the strong correlation between erroneous frames received by different nodes: the cooperators do not transmit to node *y* the entire erroneous frames but the *differences* (bits that are not equal) with respect the frame received by *y*. For reasonable values of SNR, we expect the number of erroneous bits per frame to be small, which means that if the cooperators indicate in some compressed format the bits that differ from that frame received by *y*, they will need much shorter packets than sending the whole frame.

The C-ARQ/FC operation can be described as follows: Phase 1 is identical to that in C-ARQ. Phase 2 starts when node *y* receives an erroneous frame sent by *x*. Node *y* broadcasts to its cooperators a message that contains *its erroneously received frame*; see Fig. 1.b. The cooperators will XOR bit-by-bit the frame they received from *x* and the frame sent by *y*. They code in a compressed format the position of the bits where the cooperator's frame and the *y* node's frame differ, and establish a round robin for sending this information to node *y*. If a cooperator has the correct frame, it will indicate so with a flag in the message that carries the differences. In this case the other cooperators will also receive this message with the flag set and the round robin will be stopped. If no cooperator has the correct frame, the round robin will be completed and node *y* will use this information for building the correct copy, using a frame combiner algorithm. If it does not succeed, *y* will ask for a retransmission to node *x*.

In this paper we consider a simple *majority-voting* (MV) frame combiner. The MV decision rule for obtaining a possible correct copy of the frame is the following: Let S_1 and S_0 be the sets of cooperator nodes of *y* that have detected a given bit as 1 or 0 respectively. The MV decision rule for this bit would decide 1 if $|S_1| > |S_0|$ and would decide 0 otherwise.

The average duration of the optimized Phase 2 has two different values depending on two conditions: (i) If no cooperator has a correct copy of the packet, the duration of Phase 2 is given by: $C_{Ph2}^{(1)} = T_f + (M-1) \times T_{diff}^{(2)} + T_{sig}$, where $T_{diff}^{(2)}$ is the average transmission time of the messages carrying the differences provided that the two compared frames are incorrect. (ii) If a cooperator has a correct copy of the packet, the average duration of the optimized Phase 2 is: $C_{Ph2}^{(2)} = T_f + \left(\frac{M}{2}-1\right) \times T_{diff}^{(2)} + T_{diff}^{(1)} + T_{sig}$, where $T_{diff}^{(1)}$ is the average transmission time of the messages carrying the differences provided that one of the two compared frames is correct and the other frame is incorrect. We expect $T_{diff}^{(1)} \approx \frac{1}{2} T_{diff}^{(2)} << T_f$, which means that the overhead will be clearly reduced compared with a non-optimized implementation of C-ARQ/FC as the proposed in [7].

In Table 1 we show simulation results for the average count of different bits between two frames provided that one of them is incorrect (necessary for calculating $T_{diff}^{(1)}$) and provided that both are incorrect (necessary for calculating $T_{diff}^{(2)}$), for 10,000 bit frames, different SNR values and different channel conditions (see following section for a discussion on the channel models). 10^7 iterations have been performed to calculate each average value in Table 1.

The results confirm that the overhead will be considerably reduced by using the proposed operation of C-ARQ/FC. Assume, for instance, that we send the differences indicating with $\log_2(10{,}000) \approx 14$ bits every position where the cooperator's frame differs from node *y*'s frame. For AWGN, SNRs of 5 and 3, and case (2), the cooperator will send a frame with a payload of around 300 and 2,240 bits respectively , instead of the 10,000 bit payload that would be required if the entire frame was transmitted.

Table 1: Average count of different bits between two 10,000 bit frames: (1) one of them is incorrect, (2) both are incorrect.

	AWGN		Rice (K=5)		Rayleigh	
SNR	(1)	(2)	(1)	(2)	(1)	(2)
3	63.6	159.1	266.9	517.6	734.7	1363.4
5	10.6	21.1	138.8	272.3	566.6	1068.8
10	1.2	2.4	89.6	176.2	445.8	849.5
20	1.0	2.0	94.3	188.2	388.5	748.5

III. EQUIVALENT FER EVALUATION

A. Transmission and channel models

We assume a simple receiver (BPSK modulation and an uncoded system), and we do not take into account collisions, interferences, or other incidences that can occur on real wireless networks, leaving the study of the impact of these factors on the performance to future work. In the system, we have two different types of channels:

1) Channels between x and y and its cooperators

For the *M* channels between *x* and the nodes of the set formed by *y* and its cooperators, we assume (i) independent channels with identical statistical characteristics and (ii) slow-varying narrowband fading for each channel (i.e. block fading channels). The independency assumption is justified by the fact that the distance between cooperator nodes and *y* will be of several carrier wavelengths, thus leading to independent fading; see [2]. The identically distribution assumption comes from the fact that we assume that node *y* and its cooperators are at a similar distance from *x* and suffer similar path loss and shadowing effects.

Assumptions (i) and (ii) imply that the SNR in the receivers can be modelled as independent random variables which are identically distributed for consecutive frames and/or different receivers, and which are constant during the frame reception; see [12]. These random variables follow a Rice distribution with fading parameter *K*; see [2]. The parameter *K* (a.k.a. *Rice-factor*) is the ratio of LOS signal power to the non-LOS (i.e. random multi-path component) signal power. This channel model includes as particular cases two interesting situations: (i) AWGN channel for $K \to \infty$, and (ii) Rayleigh channel for *K*=0. Note that the i.i.d. assumption for the AWGN channel, implies that for every frame all nodes will observe the *same* SNR level.

2) Channels between y and its cooperators

Considered as ideal channels with a large SNR, leading to a zero FER in transmissions between *y* and its cooperators.

B. Equivalent FER expressions

Let Q_{CARQ} and $Q_{\mathrm{CARQ/FC}}$ be the equivalent FER for C-ARQ and C-ARQ/FC protocols. For the AWGN channel we can find simple analytical expressions for this equivalent FER:

In the C-ARQ protocol, a frame will be retransmitted by *x* iif *y* and all its cooperators have received incorrectly the frame. As we have independent channels, the equivalent FER will be given by:

$$Q_{CARQ} = \left[1-(1-Q(\sqrt{2\gamma}))^{L}\right]^{M}, \qquad (1)$$

where L is the frame length, γ is the average SNR and $Q(\sqrt{2\gamma})$ is the Bit Error Rate (BER) of a BPSK receiver in an AWGN channel; see [1].

The derivation of the expression for the C-ARQ/FC protocol is more involved, and we will skip it for reasons of space. We present the expression for the case *M*=3. A frame retransmission from *x* would be needed when: (i) the *M* frame copies are erroneous, and (ii) the frame reconstruction fails. For a MV frame combiner, the frame reconstruction will fail if there is at least one bit which was erroneously received in at least *(M+1)/2* frame copies. The final expression is:

$$Q_{CARQ/FC} = Q_{CARQ} - \left(1-Q(\sqrt{2\gamma})\right)^{M\cdot L} \cdot \sum_{\substack{n_1=1..L\\ n_2=1..L\\ n_3=1..L}} \frac{L_{n_1+n_2+n_3}}{n_1!n_2!n_3!} \cdot \left(\frac{Q(\sqrt{2\gamma})}{1-Q(\sqrt{2\gamma})}\right)^{n_1+n_2+n_3} \qquad (2)$$

where $L_{n_1+n_2+n_3} \equiv L\cdot(L-1)\cdot\ldots\cdot(L-n_1-n_2-n_3+1)$.

For the more general Rice or Rayleigh channel case, we cannot obtain simple analytical expressions, as now γ itself is a random variable. We have used simulations to obtain the equivalent FER in these cases. The simulations have been performed for a frame length *L=10,000* bits, and different channel conditions ranging from an AWGN channel to a Rayleigh fading channel. 10^6 iterations have been performed for calculating each FER value. In Figures 2, 3 and 4, the results for an AWGN channel (analytical for *M=3*, simulation for *M=5*), and Rice with *K=5* and Rayleigh channels (simulation) are shown. The curves correspond to the cases *M=3* and *5*. The curve for the case *M=1* (conventional ARQ, i.e. no cooperation) is also presented as a baseline case.

Two important conclusions obtained from these figures are: (i) both C-ARQ and C-ARQ/FC achieve large improvement in terms of equivalent FER over conventional ARQ, even for *M=3*. This improvement can be of several orders of magnitude for the three different channels considered. (ii) C-ARQ/FC improves equivalent FER considerably over C-ARQ for the AWGN channel (i.e.

$K \to \infty$). For Rice *K=5* the improvement is lower. For the Rayleigh channel (*K=0*) the difference is negligible.

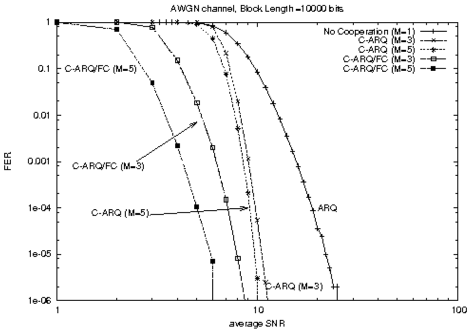


Figure 2: Equivalent FER vs SNR in an AWGN channel.

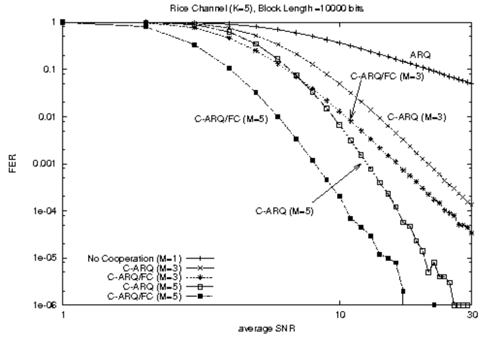


Figure 3: Equivalent FER vs SNR in a Rice channel (K = 5).

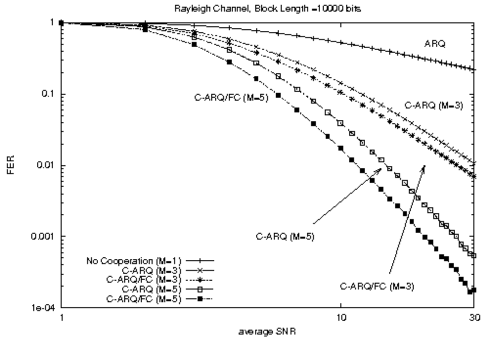


Figure 4: Equivalent FER vs SNR in a Rayleigh channel.

The first conclusion can be explained by the fact that both protocols exploit space diversity at a frame level. As long as it has *M* possibilities for receiving the frame correctly, it is normal for the equivalent FER to be greatly improved.

The second conclusion can be explained as follows: In an AWGN channel, where all receivers observe the same SNR, the dispersion of the count of erroneous bits per frame is relatively small. If the SNR is not extremely low, and under the condition that the *M* received frames are erroneous, it is highly likely that only a reduced number of error bits will appear in the *M* received frames. In this case, the Frame Combiner can be very effective in reconstructing the correct frame, as it is quite unlikely that the errors will occur in the same positions of the frame. In a Rayleigh channel, on the contrary, there is a high dispersion in the SNR values, and hence also in the count of erroneous bits per frame. Under the condition that the *M* received frames are erroneous, it is quite likely that some of the receivers will be in a deep fade condition, meaning that some of the *M* frames can have a large number of errors. In this case, the FC becomes less efficient, as it is more likely that errors will appear in the same positions of the frame.

IV. PROTOCOL EFFICIENCY

Reducing the equivalent FER is usually not the most important effect of an ARQ system. We expect that the use of an ARQ system will also have a positive impact on the *system efficiency*, defined as the maximum achievable throughput. Here we will compare the protocol efficiency achieved by the C-ARQ and C-ARQ/ FC protocols. The formula for the efficiency in both cases will be:

$$Ef = \frac{T_f}{E[n] \cdot T_{nok} + E[T_{ok}]} \qquad (3)$$

where: T_f is the transmission time of a data frame, *E[n]* is the expected number of frame retransmissions, T_{nok} is the time since *x* transmitted a frame and *y* requests a frame retransmission from *x*, $E[T_{ok}]$ is the expected time since *x* transmitted a frame and it receives a positive acknowledgement from *y*.

The considered cooperative schemes improve the equivalent FER, thus reducing *E[n]*. On the other hand, the cooperative schemes introduce a coordination overhead which increases both T_{nok} and $E[T_{ok}]$. In this formula we have neglected some parameters which may have an impact on real systems. We have not considered the processing times in each retransmission (either from node *x* or from cooperators of node *y*), and we have not taken into account the specific retransmission algorithm used by the MAC protocol. As an example, in the case of the IEEE 802.11 protocol, whenever *x* fails in its transmission to *y,* there will be two additional factors affecting the overall efficiency: (i) the exponential random backoff implemented in the case of retransmissions, and (ii) the reduction on the bit rate that also implements the protocol. The study of the impact of these factors on the protocol performance is left for future work.

Now we derive the efficiency formulas for both C-ARQ and C-ARQ/FC. For simplicity, we assume that signalling frames sent from *y* to *x* are always received correctly.

A. Expected count of frame retransmissions

Given the independency assumptions discussed in the previous subsection, the random variable *n* (i.e. count of frame retransmissions) will follow a geometric distribution, and its expected value will be: $E[n] = \frac{Q}{1-Q}$, where *Q* must be substituted by Q_{CARQ} or $Q_{CARQ/FC}$ respectively.

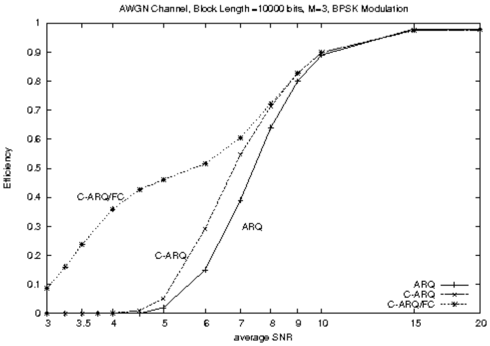
B. Efficiency of C-ARQ and C-ARQ/FC

From the description of the operation of the C-ARQ protocol given in section II we obtain: $T_{nok} = T_f + A^{(1)}_{Ph2}$, while for $E[T_{ok}]$ we have:

$$E[T_{ok}] = \frac{(1-Q)}{(1-Q_{CARQ})} \times (T_f + T_{sig}) + \frac{Q \times (1-Q^{M-1})}{(1-Q_{CARQ})} \times (T_f + A^{(2)}_{Ph2}) \cdot$$

For C-ARQ/FC the expression for T_{nok} is : $T_{nok} = T_f + C^{(1)}_{Ph2}$, while for *E[Tok]* we obtain:

$$E[T_{ok}]=\frac{(1-Q)}{\left(1-Q_{CARQ/FC}\right)}\times\left(T_f+T_{sig}\right)+\frac{Q\times\left(1-Q^{M-1}\right)}{\left(1-Q_{CARQ/FC}\right)}\times\left(T_f+C_{Ph2}^{(2)}\right)+$$
$$+\frac{\left(Q_{CARQ}-Q_{CARQ/FC}\right)}{\left(1-Q_{CARQ/FC}\right)}\times\left(T_f+C_{Ph2}^{(1)}\right)$$



Figures 5: Efficiency in an AWGN channel

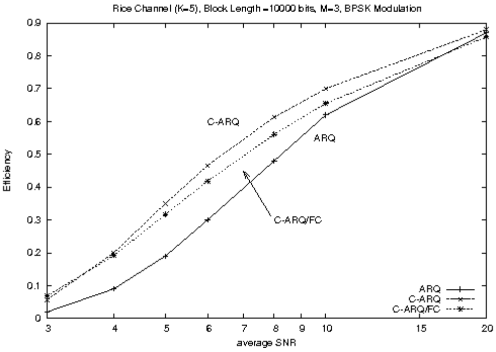


Figure 6: Efficiency for a Rice (K=5) channel.

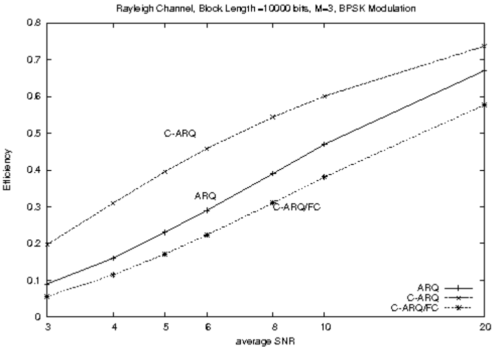


Figure 7: Efficiency for a Rayleigh channel.

C. Discussion

Figures 5, 6, and 7 show the efficiency values for ARQ, C-ARQ and C-ARQ/FC for different values of SNR and different channel models. For AWGN channel and low SNR values, when we use C-ARQ/FC, the system efficiency increases many times with respect of that of C-ARQ or classical ARQ. For instance, if SNR=5, the efficiency achieved with C-ARQ/FC is of 0.46, while for C-ARQ the efficiency drops to 0.05 and for the classical ARQ the efficiency is 0.02. Note that for SNR=5, the equivalent FER for C-ARQ/FC is several orders of magnitude lower than for C-ARQ or classical ARQ (see Figure 2), while the signalling overhead is reasonably low (see Table 1). The combined effect leads to this spectacular increase of the efficiency. The difference decreases as the SNR increases, and it is negligible for SNR values higher than 8. When the NLOS components become more important, C-ARQ becomes the more efficient mechanism. For Rayleigh channels, even classical ARQ is more efficient than C-ARQ/FC.

V. CONCLUSIONS

In this paper, we have studied the equivalent FER and the throughput for a cooperative ARQ scheme with an integrated frame combiner that exploits space diversity and cooperation between neighbouring nodes.

Our study clearly shows the advantages in terms of reduced FER and increased efficiency of the cooperative ARQ schemes. In channels with a strong LOS component and low SNR ratio, the use of a Frame Combiner increases the maximum achievable throughput many times compared with the other ARQ schemes. For NLOS scenarios, the cooperative ARQ without frame combiner achieves the best efficiency results, and the use of a Frame Combiner can even decrease the system efficiency below the classical ARQ. These results suggest that an adaptative system where nodes decide whether to use or not a frame combiner depending on the channel conditions would be an interesting alternative.

In order to focus on the essentials of the studied mechanisms, we have assumed a simple receiver, and we did not take into account collisions, interferences, backoff and retransmission algorithms, etc. These factors, however, can have an important impact on the protocol performance and are left for future work. The discussed protocols are Layer 2 mechanisms, and they do not present hardware implementation challenges. However, an efficient implementation would require major changes in the signalling mechanisms used in current MACs.

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