Collaborative ARQ in Wireless Energy-Constrained Networks *

Julián Morillo-Pozo
Computer Architecture Department
Technical University of Catalonia
Room D6-008-13 Campus Nord.
Jordi Girona 1-3, E-08034
Barcelona, Spain
+34 93 401 71 82
jmorillo@ac.upc.edu

Jorge García-Vidal
Computer Architecture Department
Technical University of Catalonia
Room C6-212 Campus Nord.
Jordi Girona 1-3, E-08034
Barcelona, Spain
+34 93 401 69 78
jorge@ac.upc.edu

Ana I. Pérez-Neira
Signal Processing and
Communications Department
Technical University of Catalonia
Room D5-201 Campus Nord.
Jordi Girona 1-3, E08034 Barcelona,
Spain
+34 93 401 64 36
anuska@gps.tsc.upc.edu

ABSTRACT

In this paper we propose a collaborative ARQ protocol that exploits diversity and collaboration between nodes in wireless networks. We show that when M neighboring nodes collaborate using the proposed scheme, they can achieve the BER versus SNR performance of an array of M' antennas provided that $M = \pi/2xM' \approx 1.57 M'$, in AWGN channels or M=2M'-1 in Rayleigh channels.

These results imply that collaborative ARQ can lead to huge savings in terms of power consumption. For instance, using BPSK in a Rayleigh channel and a target BER of 10^{-5}, the required transmission power will be reduced by a factor of x180 if M=3 nodes collaborate, while the reduction factor is about x1000 for M=5. The proposed scheme does not require any modification of RF hardware, and keeps all the complexity in the firmware that processes the packets.

We think that it can be of interest in wireless networks where hardware simplicity and power consumption are major design constraints.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *distributed networks, network communications, network topology, store and forward networks, wireless communication.*

C.2.2 [**Computer-Communication Networks**]: Network Protocols – *protocol architecture (OSI model).*

General Terms

Performance, Design, Reliability.

Keywords

Wireless network, ARQ, diversity, Rayleigh fading, AWGN, power saving.

1. INTRODUCTION

One of the most powerful techniques to mitigate the effect caused by multi-path fading in wireless channels is that of diversity reception. Diversity exploits the fact that there is a low probability that independent signal paths suffer deep fades simultaneously. An example of this is space diversity [4], in which nodes use an array of antennas separated in distance. Coherent combining of the different received signals leads to an increase of the receiver SNR (in dB) by a factor of *M'*, where *M'* is the number of elements in the array.

However, in many cases it is not realistic to assume that nodes can support multiple antennas and, therefore, that they can take advantage of the benefits of space diversity. Recently, a new class of methods in which single-antenna neighboring nodes *collaborate* in order to generate a virtual multi-antenna has been proposed, obtaining promising results (e.g. [6], [2], [8], [9]). In any case, exploiting diversity at physical layer leads to a more complex RF hardware design.

In this paper we extend the ideas of diversity and collaboration between neighboring nodes to a mechanism used in most communication stacks: Automatic Repeat Request (ARQ) [1], taking advantage of decision-based collaboration instead of data-based collaboration.

In most wired networks, packets travel following a single path from origin to destination. This path consists in general of several hops between communication nodes (hosts, switches, routers, etc). In ARQ one of these nodes keeps a (supposedly) correct copy of the packet after the packet transmission. If transmission fails, this node can retransmit the correct copy of

---

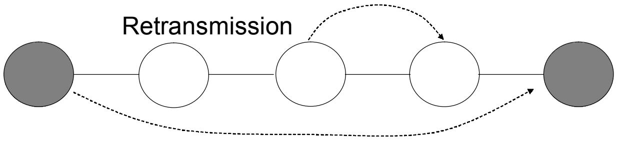
*This work was partially supported by the Spanish Government under projects TEC2004-06437-C05-05, TIC2002-04594-C02-01 (GIRAFA, jointly financed by FEDER) and by the European Commission under projects WIDENS (contract FP6-507872), EuroNGI and IST-2002-2.3.1.4 (NEWCOM).

DIALM-POMC'05, September 2, 2005, Cologne, Germany.

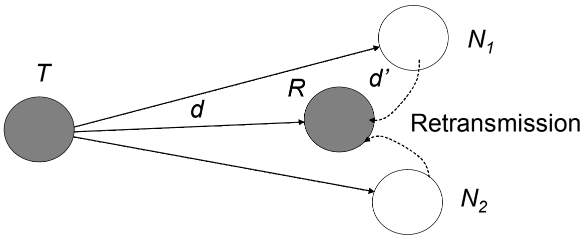
the packet again, hoping that this time the retransmission will be successful. In TCP, for instance, the node that keeps the copy of the packet is the sender host. In other protocols, such as HDLC and its derivatives, the copy of the packet is kept in the last visited node, as the packet travels through the communication path. Combinations of Forward Error Correction coding and ARQ are called Hybrid ARQ schemes [7].

In wireless networks the assumption that there is a single communication path between origin and destination is usually not true. When a node transmits a packet, due to the inherent broadcast nature of wireless media, many nodes will receive it, although most of them will discard the received packet after checking that they are not its destination. Moreover, transmission power is highly dependent on the distance: e.g. increasing distance by x10 can lead to an increase of transmission power of x10.000 for achieving the same bit error rates (BER). Another important characteristic is that in dense scattering environments, the signal decorrelates over distances of approximately one half wavelength, and due to multi-path, measured path loss in points separated one half wavelength can have differences of more than 30 dB.

In wireless transmission it can happen, for instance, that a neighboring node of the destination node correctly received a packet or part of it, while the destination node has received it with errors. It would be much more power efficient if this neighboring node delivers the copy of the packet to the final destination instead of asking for a retransmission from the originating node (Figure 1).



(a) ARQ in networks with point-to-point links



(b) Collaborative ARQ in networks with broadcast links

Figure 1: ARQ in networks with point-to-point links and broadcast links.

The scheme proposed in this paper, that we call *collaborative ARQ*, is based on the previous idea of retransmission of copies of the packet from neighboring nodes. We show that M collaborative nodes can achieve the same BER versus SNR performance as an array of M' antennas provided that $M = \pi/2\text{x}M' \approx 1.57\ M'$ in AWGN channels and $M=2M'-1$ in Rayleigh channels. These results imply that collaborative ARQ can lead to huge savings in terms of transmission power, as it achieves a diversity order of (M+1)/2.

Note that although in both cases M>M', the hardware complexity is much smaller in the case of collaborative ARQ: For the M neighboring nodes, if we use collaborative ARQ we only need M antennas (one antenna per node), while if we use space diversity we would need MxM'. Each additional antenna in a node implies the complexity of an additional RF chain and AD converter, without taking into account the need of extra processing in the node. In fact collaborative ARQ implementation only requires changes in firmware.

Collaborative ARQ, as any other collaborative scheme, is an opportunistic scheme, as only can work if node placement leads to some kind of clustering or neighborhood areas. Moreover, it can reduce throughput (or alternatively, increase latency), as the final reception of the frame in the worst case only occurs after M transmission times. We show, however, that using multilevel transmission, we can keep the same or even larger throughput than in the single antenna case, still having large power savings.

This scheme (or variants of it) can be exploited in wireless systems where hardware simplicity and power consumption are major design constraints, as is the case of wireless sensor networks.

2. THE COLLABORATIVE ARQ SCHEME

Let us assume that the distance between two nodes T and R is d. There are M-1 nodes placed at distance d' from R, with $d'<<d$. We will call these nodes "neighbors of R". We approximate the distance between T and the neighbors of R to the value d. We also assume that the channels between R, the neighbors of R and T suffer independent fading (see Figure 1).

Let T transmit a packet addressed to R, which will be received by R and its the neighbors. We assume that these nodes can identify that the final destination of the packet is R even in presence of transmission errors. After receiving the packet, every node checks for its correctness using for instance a CRC. Even if the packet was not addressed to them, or it was received with errors, nodes R and neighbors of R keep a copy of it. In case node R finds that the packet has suffered errors, it sends a signaling packet to its neighbors requesting a retransmission of their packet copies. Once R has received the information sent by its neighbors (and assuming that no received copy of the packet has a correct CRC), uses bit by bit majority voting for constructing a "hypothetical" received packet. If this reconstructed packet is still incorrect, a packet retransmission from node T is requested.

There are many possible variants to this basic mechanism. For instance, node R can ask first to its neighbors for correct copies of the packet. Only if there are no such correct copies, it would ask for incorrect copies of it. Neighbors that have suffered poor SNR values during packet reception can inhibit themselves of sending a copy (which probably has many erroneous bits). Alternatively, they can send, together with the copy of the packet, an estimation of their received SNR, so that during the majority voting process, copies with better SNR have more weight. Some form of error correction coding could be used, etc. The additional mechanisms required for determining neighbors willing to cooperate, for asking the copies of the packets, for increasing the probability of receiving a correct destination address in a packet, etc, are out of the scope of this paper.

3. THE MODEL

In this section we present a simple model to estimate the benefits and overheads of collaborative ARQ. In order to simplify the analysis, we assume that we always use majority voting in order to build a hypothetical correct copy of the packet, even in the case that a correct packet reception has occurred in either R or in its neighbors. This leads to worst case figures, but it also has the benefit of focusing our problem on the performance of the basic mechanism of collaboration and majority voting.

Let P be the BER in the transmission from T to a neighbor of R, and let P' be the BER in the transmission from this node to R. The BER at R when the neighbor node has relayed the transmission is given by

$$P_{\varepsilon} = P \cdot (1-P') + (1-P) \cdot P' \tag{1}$$

In order to simplify the model, we will assume P'<<P, having thus $P_{\varepsilon} \approx P$. Throughout our analysis we will assume a BPSK modulation scheme.

In AWGN channels, the BER for collaborative ARQ (P_{col}) is then given by:

$$P_{col} = (1-P)^{M} \sum_{i=\frac{M+1}{2}}^{M} \binom{M}{i} \left(\frac{P}{1-P} \right)^{i}, \tag{2}$$

where $M-1$ is the number of neighbors of R.

For BPSK modulation and AWGN channel [4]:

$$P = Q(\sqrt{2\gamma}), \tag{3}$$

where γ is the receiver SNR.

In Rayleigh channels, receiver SNR is a random variable. We will assume that nodes suffer independent fades, and hence we can still use (2) to obtain the overall *average* BER, substituting term P in equation (2) by the individual node average BER given by:

$$\overline{P} = \frac{1}{2} \cdot [1-\Gamma], \tag{4}$$

where

$$\Gamma = \sqrt{\gamma / (1+\underline{\gamma})} \tag{5}$$

and γ is the *average* SNR per bit.

In our analysis, we compare our scheme with the results obtained when R, instead of using collaboration, uses an array of M' antennas with *Maximal Ratio Combining* (MRC). In MRC, R coherently combines the signals before detection using an estimate of the received SNR as weight for each branch [4]. In AWGN channels, BER is given by:

$$P_{MRC} = Q(\sqrt{2M'\gamma}), \tag{6}$$

Whereas for Rayleigh channels, the average BER is:

$$\overline{P_{MRC}} = \left(\frac{1-\Gamma}{2} \right)^{M'} \cdot \sum_{m=0}^{M'-1} \binom{M'-1+m}{m} \cdot \left(\frac{1+\Gamma}{2} \right)^{m} \tag{7}$$

4. COMPARISON BETWEEN COLLABORATIVE ARQ AND MRC

We study the AWGN channel case first. For low values of γ (i.e. P close to ½), we can use the DeMoivre-Laplace approximation for the binomial distribution (see [3]), obtaining;

$$P_{col} \approx Q\left(\sqrt{\frac{M \cdot (1-2 \cdot P)^{2}}{4 \cdot P \cdot (1-P)}} \right). \tag{8}$$

Note that (8) can be also applied for Rayleigh channels, provided that we use average BER given by (4) instead of P.

The first term approximation at the origin is:

$$P_{col}(\gamma) \approx \frac{1}{2} - \frac{\sqrt{2M\gamma}}{\pi} \quad \text{if } \gamma \approx 0, \tag{9}$$

while for $M\gamma \sim 1$

$$P_{col}(\gamma) \approx \frac{1}{2 \cdot \sqrt{2M\gamma}} e^{-\frac{2 \cdot \gamma \cdot M}{\pi}}. \tag{10}$$

For MRC, we obtain the following first term approximation near the origin:

$$P_{MRC}(\gamma) \approx \frac{1}{2} - \frac{\sqrt{M'\cdot\gamma}}{\sqrt{\pi}},$$

(11)

while for M’γ~1 we get:

$$P_{MRC} \approx \frac{1}{\sqrt{4\pi M'\gamma}} e^{-M'\gamma}.$$

(12)

Comparing expressions (9)-(11) and (10)-(12) we deduce that for achieving the same BER for the same γ, we need:

$$M = \frac{\pi}{2}\cdot M' \approx 1.57\cdot M'.$$

(13)

Numerical evaluations show that (13) gives good estimates of the required *M* even for γ >> 1/*M*.

Let us examine now the case of Rayleigh channel. For collaborative ARQ, we use (8) to obtain the first term approximation at the origin:

$$\overline{P}_{col}(\gamma) \approx \frac{1}{2} - \sqrt{\frac{M\underline{\gamma}}{2\pi}}$$

(14)

For small values of *P* (i.e. $\underline{\gamma}$»1/*M*), the DeMoivre-Laplace approximation does not lead to good estimates of average BER for collaborative ARQ. In the appendix we derive the approximations:

$$\overline{P}_{col} \approx \sqrt{\frac{2}{\pi}}\cdot\frac{1}{2\sqrt{M}}\cdot\frac{1}{\underline{\gamma}^{\frac{M+1}{2}}}.$$

(15)

$$\overline{P}_{MRC}(\gamma) \approx \frac{1}{2} - \sqrt{\frac{M'\underline{\gamma}}{4\pi}}$$

(16)

if $\underline{\gamma}$ <<1/*M’* , and

$$\overline{P}_{MRC}(\gamma) \approx \frac{\sqrt{2}}{4\sqrt{\pi}}\frac{1}{\sqrt{M'}}\frac{1}{\underline{\gamma}^{M'}}$$

(17)

if $\underline{\gamma}$»1/*M’* .

Comparing expressions (14)-(16) and (15)-(17), we see that for low values of $\underline{\gamma}$, the same BER versus SNR performance is achieved provided that *M’*=*M*/2, while for larger values of $\underline{\gamma}$ need:

M’ = (*M*+1)/2.

(19)

Figure 2 gives an example of the approximations we use for comparing both schemes. We show BER versus SNR of collaborative ARQ in Rayleigh channels when *M*=9, together with the approximations given by (8), (14) and (15). In the figure we also show BER versus SNR for MRC and *M’*=5. Both curves are almost coincident.

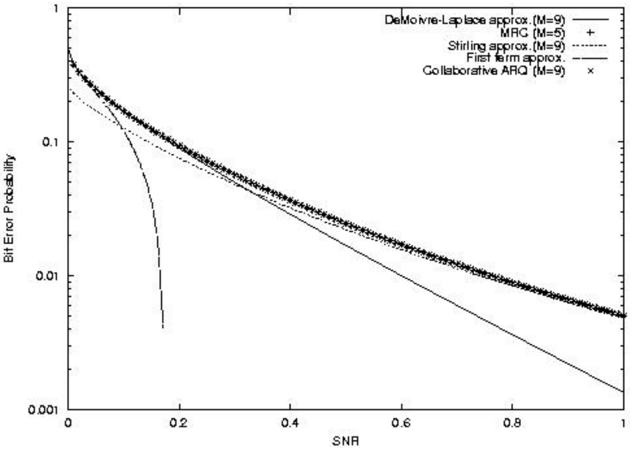


Figure 2: BER in a Rayleigh channel for collaborative ARQ with M=9 and MRC with M’=5. We also show approximations (8), (14) and (15).

Figure 3 shows that (19) gives a good estimate of the required *M* even for small values of *M* and for the whole range of $\underline{\gamma}$, having again almost coincident curves provided that *M’*=(*M*+1)/2.

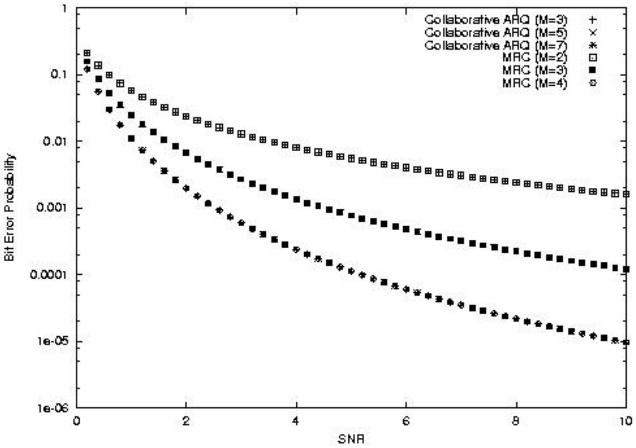


Figure 3: Bit error rates in a Rayleigh channel for collaborative ARQ and MRC for different values of M and M’. Curves for both schemes are almost coincident provided M’=(M+1)/2.

Let ρ_{col} and ρ_{nc} be the throughput for the collaborative ARQ and single-antenna no-collaborative cases, respectively. Using BPSK for both cases, we would have $\rho_{col} = \rho_{nc}/M$. We can increase throughput of collaborative ARQ using multilevel signalling. For instance, for MQAM with a constellation size of K, $\rho_{col} = \rho_{nc} x \log_2(K)/M$. As in the collaborative scheme we use now multilevel transmission, we expect that the large power gains of the collaborative scheme will be decreased. Table I shows, however, that although gains in power decrease, the collaborative scheme still leads to a great advantage in terms of both power and throughput. It is striking the case of 64-QAM, where the collaborative case obtains a throughput 20% higher with a required receiver SNR 24 dB lower than the non collaborative case.

Table 1: The first column of results shows the difference between the required receiver SNR for a BER of 10^{-5} for the single-antenna non-collaborative case (M=1) and the collaborative scheme (M=5) for Rayleigh channels. For the non-collaborative case BPSK is always used. In the collaborative case we use either BPSK and MQAM for different constellations. The second column shows the ratio between the throughput for the collaborative and the non collaborative schemes.

	SNR (M=1) – SNR (M=5)	**ρ_{col} / ρ_{nc}**
BPSK	30.2	0.2
4-QAM	30.0	0.4
16-QAM	27.5	0.8
64-QAM	24.2	1.2

5. CONCLUSIONS

In this paper we proposed an ARQ scheme that exploits space diversity and collaboration between neighboring nodes. Using simple approximation functions to the bit error rates for both collaborative ARQ and MRC, we have shown that collaborative ARQ achieves the same performance than other methods that exploit diversity at physical level. The price to pay is an increment on the number of elements/nodes needed to obtain the same performance. It is an interesting fact that very simple expressions for this overhead can be found for the cases of AWGN and Rayleigh channels.

The proposed scheme can use simple RF hardware, and keeps all the complexity in the firmware that processes the packets. We think that it can be exploited in energy-constrained wireless networks, as is the case of wireless sensor networks.

As further work we plan:

- to study and elaborate variants of the mechanism, as for instance looking for thresholds in received SNR so that a neighbor can decide whether to retransmit or not a received frame,
- to study the impact of channel coding in the obtained results, and
- to investigate extensions of the proposed collaborative ARQ to diversity schemes other than spatial, and impact on the MAC design.

This paper is an example of how multi-path mitigating techniques developed in the physical layer can be extended to upper layers of the stack.

6. APPENDIX

We will first proof (15). Defining

$$\alpha = \frac{\overline{P}}{1-\overline{P}}, 0 \le \alpha \le 1$$

and using Stirling's approximation for the factorial, we get:

$$\overline{P}_{col} \approx$$

$$\frac{\left(1-\overline{P}\right)^{M} \alpha^{\frac{M+1}{2}} 2^{M+1}}{\sqrt{2\pi} M^{\frac{1}{2}}} x$$

$$\sum_{k=0}^{\frac{M-1}{2}} \frac{\alpha^{k}}{\left(1+\frac{2k+1}{M}\right)^{\frac{M}{2}+k+1} \left(1-\frac{2k+1}{M}\right)^{\frac{M}{2}-k}}$$

For $0 \le k \le M/2$ we have (assuming M≥3):

$$e^{-k} / \left(1-\frac{2k+1}{M}\right)^{\frac{M}{2}-k} \le (1-1/3)^{-3/2} \approx 1.8371$$

and

$$\left(1+\frac{2k+1}{M}\right)^{-\frac{M}{2}-k-1} \le 1.$$

Hence (assuming M≥3):

$$c \le \sum_{k=0}^{\frac{M-1}{2}} \frac{\alpha^{k}}{\left(1+\frac{2k+1}{M}\right)^{\frac{M}{2}+k+1} \cdot \left(1-\frac{2k+1}{M}\right)^{\frac{M}{2}-k}} \le$$

$$\le c + 1.8371 \frac{e\alpha}{1-e\alpha}$$

Where c = $(1+1/3)^{-3/2-1}(1-1/3)^{-3/2} \approx 0.8949 \approx 1$. Finally, for small α we obtain:

$$\overline{P}_{col} = \sqrt{\frac{\overline{P}}{1-\overline{P}}}\sqrt{\frac{2}{\pi M}}\left[4\overline{P}\left(1-\overline{P}\right)\right]^{\frac{M}{2}} \tag{20}$$

and

$$\overline{P}(\gamma) \approx \frac{1}{4}\cdot\frac{1}{\underline{\gamma}}.$$

Arriving thus to (15).

In (16) we use the following identity:

$$\sum_{k=0}^{M'-1}\binom{M'-1+k}{k}\cdot\frac{1}{2^k} = 2^{M'-1}, \tag{21}$$

and the approximation for large *M'*:

$$\sum_{k=1}^{M'-1}\binom{M'-1+k}{k}\frac{k}{2^k} \approx M'2^{M'-1}\left[1-\frac{1}{\sqrt{\pi M'}}\right] \tag{22}$$

Identity (21) can be derived, for instance, using $P_{MRC}(0)=1/2$ in (7). Approximation (22) is then easily obtained, using Stirling's approximation. Using (21) and (22) we get:

$$\overline{P}_{MRC}'(0) \approx -\frac{M'}{2}+\frac{M'}{2}-\frac{M'}{2\sqrt{\pi M'}} = \sqrt{\frac{M'}{4\pi}}$$

7. REFERENCES

[1] D. Bertsekas, R. Gallager, "Data Networks" (Second Edition), *Prentice Hall International Editions*, *1992.*

[2] S. Cui, A. J. Goldsmith and A. Bahai, "Energy-efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks" , IEEE Journal on Selected Areas of Communications, Vol. 22, No. 6, August, 2004.

[3] W. Feller, "An Introduction to Probability Theory and Its Applications" (3rd Edition), *John Wiley and Sons*, 1957.

[4] A. Goldsmith: "Wireless Communications", Cambridge University Press, 2005.

[5] P. Larsson "Selection Diversity Forwarding in a Multihop Packet Radio Network with Fading Channel and Capture", *Mobile Comp. Commun. Rev.,* vol. 5, no. 4, Oct. 2001, pp. 47-54.

[6] J. N. Laneman and G. W. Wornell, "Distributed Space-Time-Coded Protocols for Exploiting Cooperative Diversity In Wireless Networks", *IEEE Trans. Info. Theory,* vol. 49, no. 10, Oct. 2003, pp. 2415-25.

[7] S. Lin, D. Costello, M. Miller, "Automatic-Repeat-Request Error-Control Schemes" , IEEE Communications Magazine, Vol. 22, No. 12, December 1984.

[8] A. Nosratinia, T.E. Hunter and A. Hedayat, "Cooperative communication in wireless networks", *IEEE Communications Magazine,* vol. 42, no. 10, October 2004, pp. 68-73.

[9] A. Sendonaris, E. Erkip, B. Aazhang, "User Cooperation Diversity- Part I: System Description", IEEE Transactions on Communications, Vol. 51, No. 11, November 2003.