IMPACT OF SR-ARQ WITH FINITE BUFFER ON TDD/TDMA WIRELESS LAN

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Abstract In this paper, the influence of some implementation parameters of Selective Repeat Automatic Repeat Request (SR-ARQ) on system performance is investigated. In the framework of the specific SR-ARQ algorithm specified by the ETSI BRAN HIPERLAN/2 (H/2) Wireless LAN standard, the need for optimizing the ARQ signalling bandwidth is illustrated and several signalling strategies are presented. Even with optimum management of the signalling bandwidth, the finite transmit and receive buffers can seriously limit the throughput. This effect is modeled by using a simple probabilistic approach, relying on the TDD/TDMA access scheme, and is evaluated by simulation. The interaction of SR-ARQ with scheduling and Link Adaptation is also discussed and finally, an ARQ aware scheduling strategy is proposed.

Keywords: Wireless LAN, HIPERLAN/2, ARQ, SR-ARQ, scheduling, Link Adaptation

1. Introduction

Any communication system implements mechanisms for limiting the transmission of erroneous messages. These techniques can be sorted in two main categories depending on their using error-correcting or error-detecting codes. In the latter, if a receiver detects an erroneous packet, it sends a message back to the transmitter to signal the error.

The scheme used by such a system is called Automatic Repeat Request (ARQ). Many instanciations have already been thoroughly studied (Lin and Costello, 1983), (Gibson, 1997). They range from the stop-and-wait to the selective repeat (SR) algorithms. This paper just focuses on the latter. Indeed, the SR scheme provides efficient retransmission with a limited overhead of acknowledgment and a reasonable delay: only the erroneous packets which are negatively acknowledged or for which the time out has expired are repeated. This implies that buffers must be provided at both the transmitter and receiver side in order to store the not yet positively acknowledged packets.

In this paper, three issues related to the SR-ARQ are addressed: the signalling strategy, the limitations due to the finite transmitting or receiving buffer and the impact of the scheme on the scheduling and on the Link Adaptation (LA).

In (Li et al., 2000), the authors study the signalling mechanism of an SR-ARQ scheme in the framework of H/2 Wireless LAN. They show that, in the case of a downlink (DL) connection, an incremental allocation of the ARQ acknowledgment messages optimizes the throughput on the Data Link Control (DLC) layer. In the case of an uplink (UL) connection, we show in section 2 that the algorithms can be further improved if the exact required number of feedback messages is dynamically granted. We then compare various algorithms for DL or UL connections, and select the most efficient one. With this first step, a strategy is proposed to optimist the throughput with respect to the signalling constraints in the case of an H/2 based network.

Nevertheless, a limitation in the throughput can still be observed even for large buffer sizes when the Packet Error Rate (PER) grows. In section 3, we model the phenomenon with simple discrete probabilities calculus, relying on a TDD/TDMA access scheme, which differs by the approach and the assumptions from what can be found in (Miller and Lin, 1981), (Saeki and Rubin, 1982) or (Jianhua et al., 1999). The analytical approach is compared with results simulated with a H/2 network simulator.

To complete the study of the SR-ARQ scheme with a finite buffer size, section 4 evaluates its impact on the scheduling and the LA. Actually, the scheduling of resources has already been studied in papers like (Kadelka et al., 1999) or (Ranasinghe et al., 2001) for TDD/TDMA based systems. These studies are yet limited to alternatives of round robin algorithms without involving ARQ parameters. We propose here to explain to what extent the choice of some ARQ parameters can greatly influence the choice of a scheduling algorithm and thereof the resulting overall system performance. We will show that a meticulous setting of the parameters is key to avoid a drop in throughput. Simple guidelines can be drawn out of this study. Based on these results, a scheduling strategy is proposed. In the same way, the Link Adaptation (LA) (Goldsmith and Chua, 1998), (Simoens and Bartolomé, 2001) needs some slight tuning in order to take the ARQ into account. This issue is also discussed in section 4.

2. Signalling strategies of SR-ARQ in H/2

Signalling in H/2. In H/2, the Medium Access Control (MAC) frame structure relies on a TDD/TDMA subdivision (Kadelka et al., 1999), (ETSI/BRAN/DLC, 2000). The frame lasts 2 ms and splits into Broadcast, DL, Direct Link (DiL) and UL. During the DL phase, the Access Point (AP) sends Packet Data Unit (PDU) trains either in multicast or to a specific Mobile Terminal (MT). In the DiL phase, MTs send PDUs to each others in a peer-to-peer manner (this will not be considered in what follows). Lastly, MTs send PDU trains to their AP during the UL phase. This is illustrated in figure 1.

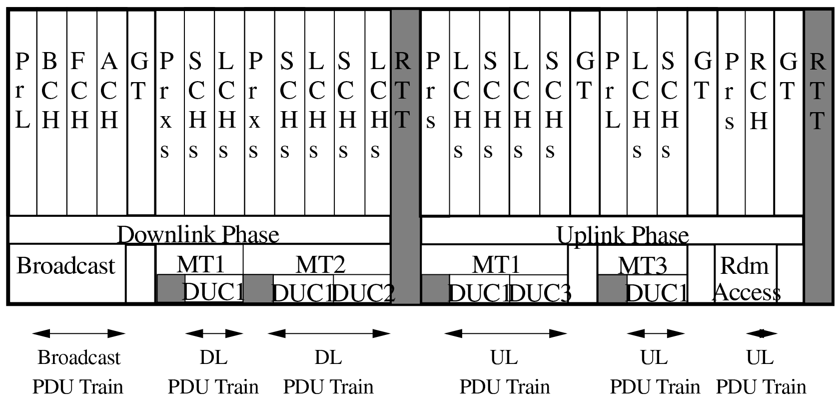

Figure 1. HIPERLAN/2 MAC frame layout

A given MT can manage several connections either DL or UL. If a DL connection is considered, the AP sends Long transport CHannels (LCHs) containing payload to the MT and the latter acknowledges the receipt of the packets in Short transport CHannels (SCHs) containing ARQ feedback messages. In these messages, the MT can request more bandwidth for acknowledgement using the ABIR bit (Arq Bandwidth Increase Request). If an UL connection is considered, the MT sends the payload in LCHs and the acknowledgement is done in SCHs sent by the AP. In both cases, as the resource allocation is centralized, the scheduler in the AP grants the number of LCHs and SCHs for each connection. To get the resources, the MT makes its request via a Random access CHannel (RCH) or an SCH. Thus, for limiting the overhead and for the buffer management, an adequate choice of the signalling strategy is key.

This section deals with the choice of the strategy. This will be H/2 oriented but the algorithms can be extended to any other system relying on a TDD/TDMA access scheme.

Signalling strategy algorithms. As illustrated in table 1, several algorithms can be envisaged either for a DL or for an UL connection. For all these algorithms, the scheduler grants dynamically the number of SCHs (they can vary from frame to frame) and the maximum number of SCHs can be fixed or not. Let outline their principles.

Table 1. Signalling strategies

	Strategy name	Connection type	Comments
1	*ABIR based*	DL	dynamic allocation according to the ABIR
2	*upper boundary*	UL	dynamic allocation but limited to a maximum value
3	*no boundary*	UL	dynamic allocation without limit

The ABIR based algorithm is close to the one proposed in (Li et al., 2000). Indeed, when the AP receives an ARQ Feedback Message (ARQ FM) with the ABIR bit set, the number of SCHs is increased by one the frame after with no upper limit. Otherwise, this number is decreased by one. Yet, this value is kept greater than one.

In the case of the second algorithm, the scheduler grants all the needed ARQ FM to the connection up to a given limit denoted Max. We tested this scheme for Max ranging from 1 to 3. This limits the overhead with a highly dynamic bandwidth.

The third algorithm is an extension of the second with no upper limit. This may grow the overhead but the scheme responds to any variation of the traffic with no delay.

The performance of these three algorithms is compared in terms of throughput calculated on top of the DLC layer (i.e. provided to the IP layer). Before dealing with the simulation results, let first derive an expression for the ideal throughput.

Analytical ideal approach of the throughput. Based on the H/2 MAC overhead calculation of (Kadelka et al., 1999) and the ideal ARQ study of (Lin and Costello, 1983), the H/2 throughput on top of DLC layer is given by:

$$\rho_{[Mbps]} = r_{mode[Mbps]} \cdot (1 - \frac{\tau_{overhead}}{\tau_{frame}}) \cdot \beta \cdot (1 - PER) \qquad (1)$$

where

. r_{mode} is the nominal bit rate ranging from 6 to 54 (Mbps) depending on the physical mode selected for the transmission of the LCHs (ETSI/BRAN/DLC, 2000)

- $\tau_{overhead}$ is the part of the MAC frame containing no payload. Referring to (Kadelka et al., 1999) and (ETSI/BRAN/DLC, 2000), this is worth

$$\tau_{overhead[\ \mu s]} = 146_{[\ \mu s]} + \tau_{SCHs[\ \mu s]} \tag{2}$$

  The duration of the SCHs also depends on the physical mode used by the LCHs. Also note that the MAC overhead includes propagation delays (guard times).

- τ_{frame} equals 2 ms

- β represents the overhead ratio introduced by the Cyclic Redundancy Check (CRC) bits (ETSI/BRAN/DLC, 2000) and the Convergence Layer (CL) header (ETSI/BRAN/CL, 2000). This value is worth

$$\beta = \frac{48}{54} \tag{3}$$

- PER is the Packet Error Rate ranging from 0 to 20% in our simulations, which corresponds to typical operating conditions.

Equation (1) reflects ideal ARQ assumptions that is an infinite buffer size, an unlimited number of retransmissions, error-free signalling and no signalling bandwidth limitation. Ideal ARQ assumptions are not realistic but will provide an upper bound to the throughput. Finally, packet errors are assumed independent. In the H/2 context, such an assumption is valid in noise-limited environments, where thermal noise produces bit error bursts at the output of the Viterbi decoder which are much shorter than the packet length.

Simulation results. The throughput obtained during the transmission of data between one AP and one MT, with one connection activated (either UL or DL) and full system load (large file transfer) is depicted on figure 2. In this simulation, the transmitter or receiver buffer has a window size of 512 and the payload is transmitted with the fastest mode ($64-QAM$), which gives a nominal bit rate of 54 Mbps.

From figure 2, several observations can be driven:

- the second algorithm gives better results for higher values of Max; this is natural since the retransmission of the packets is faster so that the new arriving packets are transmitted faster as well;

- as no limit is set on the number of SCHs, the third algorithm performs even better; even though the non limited overhead can be fatal to the throughput, it is observed that under these circumstances, the number of SCHs is regulated and does not exceed 8 or 9;

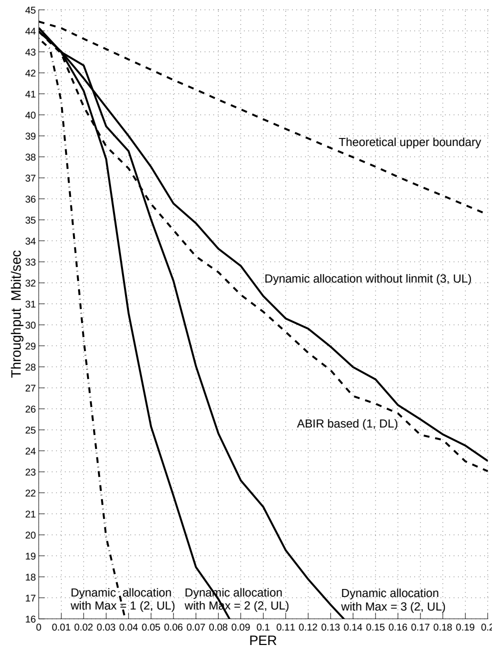

Figure 2. Throughput vs. PER for different signalling algorithms

. the first algorithm (using the ABIR bit in a DL connection) reaches a comparable performance provided that the maximum number of SCHs is not limited; as this scheme does not respond as fast as the third one, we obtain a throughput which is slightly inferior.

Note that for other sources of traffic (like VBR - Variable Bit Rate), the algorithm ranking is expected to be similar but potentially with larger gaps between the throughput curves. For instance, if a VBR traffic source is used, the third algorithm will be better suited to the dynamic of the traffic than the first one.

Nevertheless, even with the best fitted scheduling algorithm, the discrepancy between the theoretical curve obtained with ideal hypothesis on the ARQ and that obtained with the simulation is rather large. This phenomenon is explained in the next section.

3. Influence of a finite buffer on ARQ

This section analyzes the effect of finite buffer space on the throughput performance of SR-ARQ. As stressed on figure 2, when the PER increases, the throughput obtained by simulations becomes significantly lower than that computed using expression (1). The issue of SR-ARQ under limited buffer space has already been investigated in several papers. Generally (e.g. (Miller and

Lin, 1981)), the transmission of packets and the reception of acknowledgements can occur simultaneously, which cannot be assumed in a TDD/TDMA access scheme. In (Saeki and Rubin, 1982), the analysis of SR-ARQ with TDMA is restricted to messages of one packet. (Jianhua et al., 1999) provide a method called "sequential method" to compute SR-ARQ throughput. Here we derive an approximation of the throughput by simple discrete probabilities calculation, assuming a TDD/TDMA scheme with multiple packets transmitted per frame. Then we compare it to simulation results in the H/2 context.

Derivation of analytical throughput expression. The same assumptions as in section 2 hold, except that now the buffers are of limited size W at transmitter and receiver side. Furthermore, the following behavior of the SR-ARQ algorithm is supposed:

- The new packets are sent with ascending sequence number. Including the retransmissions, M packets are allocated to the connection per frame. We assume $M \leq W$.
- Let i be the index of the oldest packet not yet positively acknowledged. It is allowed to free only the packets of index smaller than i.
- Only packets of sequence number smaller than $i+W$ can be sent. Therefore, it can happen that less than M packets are transmitted in a frame, or even no packet if the buffer is full. This results in a stalled connection.
- There is no ARQ signalling bandwidth limitation.

In order to isolate the buffer saturation effect, we compute the efficiency coefficient χ defined as the ratio between the observed throughput and the ideal ARQ throughput: $\chi \hat{=} \frac{\rho_{\text{effective}}}{\rho_{\text{ideal}}}$. The calculation of χ is made by considering a block of M packets, transmitted at a time when the transmission is not stalled. The maximum age that the block reaches is denoted by N ($N = 1$ if every packet of the block is correctly received at the first attempt). If $N \geq 2$, denote by n $(1 \leq n \leq M)$ the index of the oldest (i.e. having the smallest sequence number) erroneous packet at age $N-1$. The block will be responsible for a transmission stall if all the following conditions are true:

1) $N \geq 2$

2) There is no block in the buffer older than N (otherwise, there would be a transmission stall, but the considered block would not be responsible for it).

3) $NM-(n-1) > W$ (at age N, only $n-1$ packets have already been freed)

We consider the contribution of each block to the average efficiency χ. If the block does not produce any transmission stall, then the associated efficiency equals 1. Otherwise, it equals $\frac{M}{M+NM-(n-1)-W}$.

An analytical expression of χ is derived in appendix and is plotted on figure 3 versus simulation results obtained with the H/2 network simulator. The model matches the simulation results with good accuracy. Yet, when $\alpha \hat{=} \frac{M}{W}$ grows, the buffer saturation occurs more frequently and the assumption that blocks are of size M is no longer valid. Also, some implementations specific to the H/2 standard can be accounted for minor differences. Still, the validity of the assumptions is credited by the similarity of the curve shapes: the efficiency at a given PER decreases when the ratio $\alpha \hat{=} \frac{M}{W}$ approaches 1. At common PER values (below 15 %), the efficiency remains high (above 95 %) when α is below 30 %. This can have an impact on resource allocation as explained in next section.

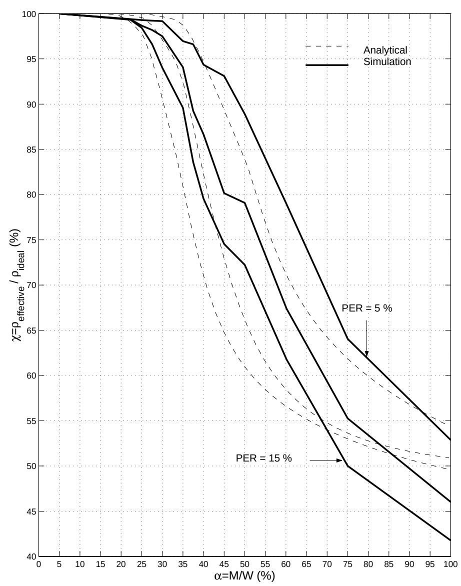

Figure 3. Illustration of the stall phenomenon for PER=5,10 and 15 %

4. ARQ impact on some layer-2 algorithms

Description of some scheduling algorithms. In this section, the impact of SR-ARQ on two specific scheduling algorithms is investigated. This analysis is mainly based on two simple scheduling techniques described in (Kadelka et al., 1999) in the H/2 context and illustrated in figures 4a and 4b.

More sophisticated techniques exist in the literature. For instance, (Ranasinghe et al., 2001) optimize the resource allocation by classifying the terminals and by using the dual queue method. In general, it is possible to trade off fairness between terminals and connections against maximum throughput in the cell.

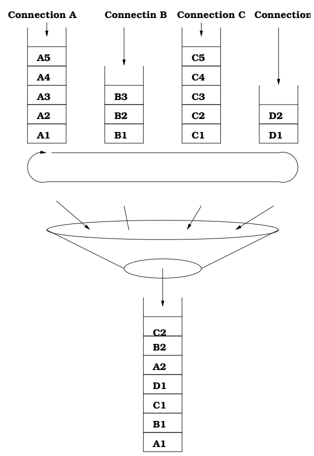

Figure 4a. Non Exhaustive Round Robin Algorithm (NERR)

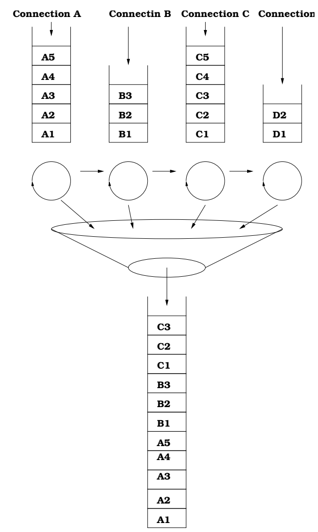

Figure 4b. Exhaustive Round Robin Algorithm (ERR)

For instance, the following algorithms are classified by fairness and throughput efficiency in figure 5:

. best-SNIR ERR: the connection having the best Signal to Noise plus Interference Ratio is served first - this implies a high throughput but the slowest connections may never be served;

. time-based NERR: the scheduler allocates the same duration for each connection no matter what their modulation is - even the slow connections will be served;

. data-based NERR: the scheduler allocates the same amount of data for each connection - this will provide the fairest algorithm at the expense of the cell throughput. In the following NERR will stand for this algorithm.

Let now see how we can choose a scheduling algorithm based on the ARQ configuration used.

Impact of ARQ on the resource allocation. In order to illustrate the influence of ARQ on resource allocation, figure 6 plots the throughput of two H/2 connections in $64-QAM$ mode (54 Mbps nominal bit rate) at full load

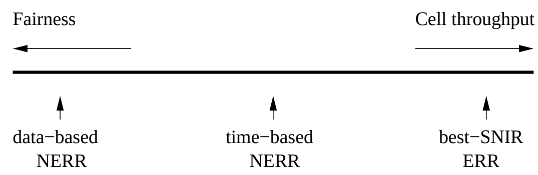

Figure 5. Comparison between various scheduling algorithms

versus PER with a fixed ARQ window size set to 512 and served by NERR. The total throughput almost reaches the ideal ARQ upper-bound. As a reference, the throughput obtained in the same conditions but with a single connection is also plotted. The latter can be viewed as a "worst case" of what can be reached in the multi-connection case when only one connection is served per frame, and all connections are stalled simultaneously. Basically, NERR performs very well because the ratio α (cf. section 3) was divided by two.

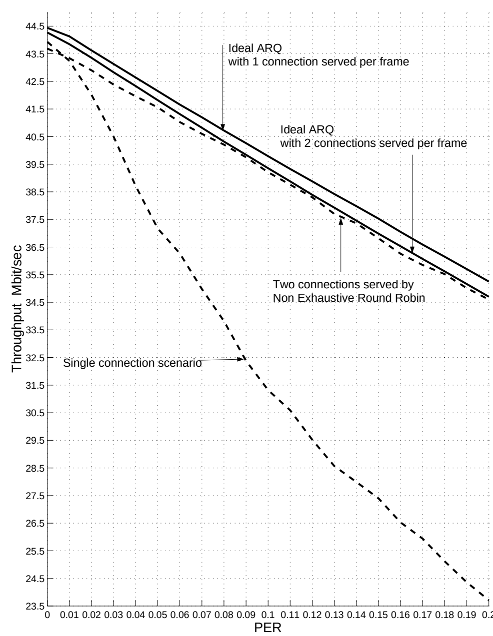

Figure 6. Throughput of 2 active twined connections served by NERR

Now this phenomenon has been clearly highlighted, let see how this translates into recommendations for tuning scheduling algorithms. For that purpose, let consider simulation results plotted on figure 3. If a throughput efficiency greater than 98% is imposed, with a PER of 10%, α needs to be less than 28%. For simplification sake, the scenario is restricted to *n* identical connections, each set to the same physical mode φ (from 0 for *BPSK* rate $\frac{1}{2}$ to 6 for $64-QAM$ rate $\frac{3}{4}$). If each frame is completely filled, the number of LCHs per frame is thus related to the physical mode. A relation between φ, n and the window size W can therefore be derived as represented on figure 7.

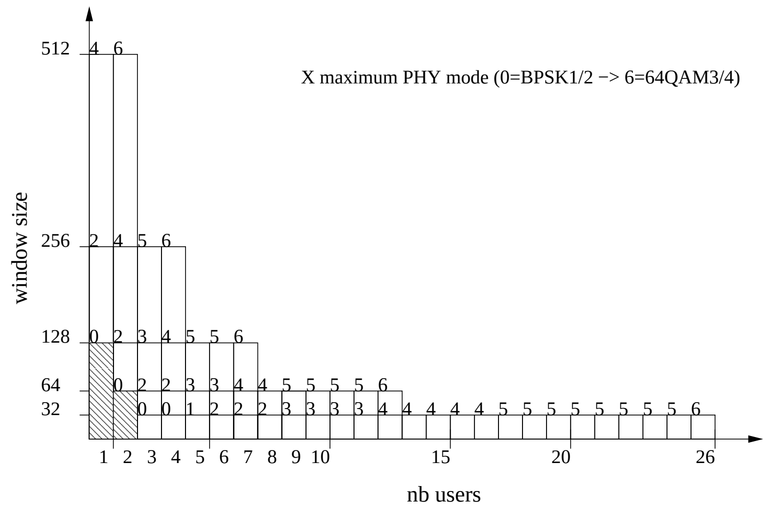

Figure 7. Maximum physical mode to use for a given number of users and a given window size

This graph can be read in the following manners:

- if we have one user in the cell, we cannot have a WS smaller than or equal to 64;
- if we have several users in the cell, all in physical mode 5 (36 Mbps) and with a WS of 128, then this number of users must be greater than or equal to 5;
- if all the users have a WS of 32 and a physical mode 6 (54 Mbps), there needs to be at least 26 users in the cell;
- if 4 users share the cell with the 6^{th}physical mode (54 Mbps), WS has to be greater than or equal to 256;
- if 7 users share a cell with a WS of 64, then their physical mode should not exceed 4 (27 Mbps);
- if all connections have a physical mode 5 and a WS of 64, the optimum number of users in the cell using a NERR algorithm is 9.

An ARQ aware scheduling strategy proposal. The above results and figure 5 suggests the following algorithm to allocate resources in a TDD/TDMA access based network. Connections are gathered in groups sharing similar QoS defined by a priority (figure 8). These groups are served by ERR (priority order) and among each group, the connections are served by NERR. If the conditions shown on figure 7 are met, the throughput efficiency in the cell can reach 98 %. We can go further by referring to (Kadelka et al., 1999) where the authors show that the number of users served by NERR must be minimized in order to limit the MAC overhead. Since figure 7 provides a lower limit λ for the number of users per group, we can thus impose an upper limit Λ to reduce the overhead. For instance, the QoS based priority groups can be further divided into sub-groups (of $\lambda <$ nb users $< \Lambda$) served by NERR. These sub-groups being served by a fair ERR, in which the first served group changes cyclically. For clarification sake, let consider the simplistic hypothesis which led to figure 7, if all users have a window size of 128 and are transmitted in physical mode 5, λ equals 5 and the optimum number of users in the cell can be taken equal to 5. Note that such an algorithm is not simulated in this paper and is currently under evaluation.

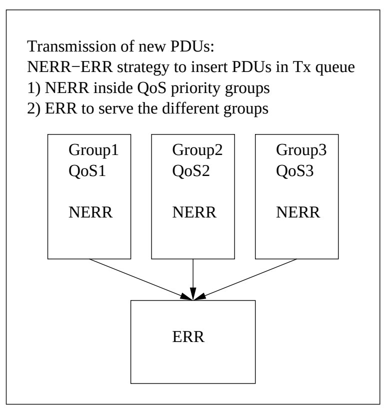

Figure 8. Scheduling algorithm proposal for a TDD/TDMA access based WLAN

Impact of SR-ARQ on Link Adaptation. Link Adaptation is a technique that has been extensively studied (Goldsmith and Chua, 1998): it consists in adapting the constellation size and the coding rate to the fluctuating link quality. For instance, when the estimated PER exceeds a pre-computed threshold, a more robust physical mode (i.e. the association of a coding rate and a constellation) is selected with a lower nominal data rate but a higher throughput in the current transmission conditions. A measure of the link quality can be the PER. In the H/2 context (Lin et al., 2000), (Simoens and Bartolomé, 2001), the physical mode switching points correspond typically to a PER of 30 % and are computed assuming ideal ARQ. However, as illustrated on figure 2, the throughput with non-ideal ARQ can be much lower than that of ideal ARQ at such PER values. Therefore, the thresholds computed assuming ideal ARQ can lead to a wrong behavior of LA algorithm and a significant throughput degradation. This problem can be partially solved by carefully designing the resource allocation algorithm, as explained before. A simple solution, which is often proposed in the literature, consists in taking some margin in the switching points (at the expense of a slightly sub-optimum throughput performance) so that for instance the PER never reaches 30 % but rather 5 %.

5. Conclusion

In this paper, two SR-ARQ signalling strategies well adapted to TDD/TDMA access based systems either for an UL or for a DL connection are proposed. Nevertheless, a gap is observed between the theoretical throughput and the one obtained by simulation in a H/2 network. We then develop an analytical approach to derive a new formula for the throughput which takes the finite buffer into account. By doing so, we verify that finite buffer space is a major factor limiting the throughput of the SR-ARQ scheme. We also show that the throughput loss can be recovered by carefully setting ARQ buffer size of each connection, modifying the link adaptation switching points and carefully designing resource allocation algorithm.

Appendix: Derivation of analytical throughput efficiency expression

With the definitions of section 3, the first thing to compute is p_{N_0,n_0} the probability of the event ($N = N_0 \geq 2$ and $n = n_0$). An intermediate result is the probability of event A « a given packet of index m is correctly received to the latest at age N_0 », which of course does not depend on m since packet errors are independent.

$$p(A) = \sum_{j=1}^{N_0} p(A_j) \tag{A.1}$$

with A_j the event: « Packet number m is not received correctly at age $< j$ and is received correctly at age j ». We have $p(A_j) = \varepsilon^{j-1}(1-\varepsilon)$ where ε denotes the PER. Thus (A.1) can be rewritten as:

$$p(A) = (1-\varepsilon)\sum_{j=1}^{N_0} \varepsilon^{j-1} = (1-\varepsilon)\frac{1-\varepsilon^{N_0}}{1-\varepsilon} = 1-\varepsilon^{N_0} \tag{A.2}$$

The event ($N = N_0$ and $n = n_0$) can be expressed as $B \bigcap C \bigcap D$ with:

. B: «the first $n_0 - 1$ packets of the block are correctly received to the latest at the $(N_0 - 1)^{th}$ transmission »
$p(B) = (1-\varepsilon^{N_0-1})^{n_0-1}$

. C: «the n_0^{th} packet is correctly received at N_0 and not before »
$p(C) = \varepsilon^{N_0-1}(1-\varepsilon)$

. D: «the $M - n_0$ remaining packets are correctly received to the latest at N_0 »
$p(D) = (1-\varepsilon^{N_0})^{M-n_0}$

Since packet errors are independent, events B,C and D are also independent. Therefore, $p_{N_0,n_0} = p(B)p(C)p(D)$. Having p_{N_0,n_0}, the expression of χ is direct:

$$\chi = p(N=1) + \sum_{\substack{N_0 \geq 2 \\ 1 \leq n_0 \leq M \\ N_0 M - (n_0-1) \leq W}} p_{N_0,n_0} + \sum_{\substack{N_0 \geq 2 \\ 1 \leq n_0 \leq M \\ N_0 M - (n_0-1) > W}} p_{N_0,n_0}\left(\frac{M}{M + N_0 M - (n_0-1) - W}\gamma(N_0) + 1 - \gamma(N_0)\right) \tag{A.3}$$

With $p(N=1) = (1-\varepsilon)^M$ and

$$\gamma(N_0) = \prod_{i=0}^{+\infty}(1-\varepsilon^{N_0+i})^M \tag{A.4}$$

The equation A.3 reflects the three conditions necessary to produce a transmission stall as described in section 3. $\gamma(N_0)$ is the probability of the second event: «There is no block in the buffer older than N_0 ». This means that the block sent just before the considered block was received correctly at age N_0 and that the block sent before the previous one was received correctly at age $N_0 + 1$ and so on. Since blocks are independent just like packet errors are, $\gamma(N_0)$ is the product of these probabilities as written in A.4.

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