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Signal Processing 86 (2006) 1755–1772

SIGNAL PROCESSING

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Optimization of wireless communication systems using cross-layer information

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Received 3 January 2005; received in revised form 15 September 2005; accepted 15 September 2005
Available online 21 December 2005

Abstract

In the last few years, a new design paradigm has arisen in the field of wireless communications research: the so-called cross-layer optimization. In fact, this paradigm implies the redefinition of the overall design strategies for this kind of systems as it breaks the classical OSI model. The endless need for higher and higher bit rates, stringent QoS requirements and anytime-anywhere connections for wireless systems leads to the necessity of squeezing to the utmost the available radio bandwidth. Cross-layer plays a key role to achieve this goal. The amount of literature about this issue is still relatively scarce, but the premier published results show that the potential obtainable gains are worthy to deserve the increasingly attention that cross-layer is getting. This paper revises the different definitions used for such paradigm, describes the possible mechanisms that can be fitted into the definitions, outlines research challenges to meet in the near future, and analyses different strategies proposed by the authors showing some recent novel results for CDMA-based and WLAN systems.

Keywords: Wireless communications; Cross-layer; MAC protocols; CDMA; WLAN

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1. Introduction

The OSI model is a widely known well-accepted framework for communication systems [1,2]. This model is based on the Shannon separation principle which is known to be appropriate for many practical applications. With this model, systems are decomposed in seven layers (physical–link–network–transport–session–presentation–application). Each one of them is responsible of a sub-set of the operational functions of the system. Messages are interchanged between entities of the same layer in both transmitter and receiver. Each layer is aware of its own layer messages, it embeds its information into upper layer messages when messages go down in the layer stack and it discards the lower layers information when messages go up.

This model has proved to be quite useful for developing smart algorithms and techniques for different communication systems, achieving proper working mechanisms. Considerable research efforts have been put into improving the efficiency of individual layers. At the physical layer (PHY), advanced signal processing techniques have been devised to face problems such as noise, interference

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doi:10.1016/j.sigpro.2005.09.029

and unwanted signal replicas caused by the random and time-varying nature of radio channels [3–5].

Besides, a great variety of medium access control (MAC) schemes have been developed for wireless systems. In particular, two innovative aspects have been taken into account when designing MAC protocols for 4G systems: the packet switched nature of multimedia communications and the need to fulfil service-dependent QoS requirements [6–13].

At link layer, several ARQ and FEC mechanisms have been developed and studied in order to operate in wireless communication systems [14–19].

The inherent mobility of the communication nodes in wireless systems must be carefully considered in the design of network and transport layers. Indeed, these layers are key pillars of wireless networks as they must guarantee anywhere seamless end-to-end connections. For example, TCP is a widely used transport protocol whose impact in a wireless environment has been recently studied [22]. Routing protocols are one of the widest studied areas for wireless communication systems [20,21].

However, advances attained in the different layers have barely taken into account those achieved in other layers. Actually, since a few years ago, each layer research has widely ignored the other layers. It seems clear that system performance improvements could arise from some communications between different layers, having in mind in the system design certain smart interaction between them. This foresight has led to a new paradigm: cross-layer optimization.

Fig. 1 shows the OSI-layered model and a subset of the possible cross-layer interactions that can be considered when performing a cross-layer design. This graph allows making out the vast field of research to explore in this area.

As an example, Fig. 2 shows with arrows the different control flows needed to provide a cross-layer interaction between physical and upper layers of two remote nodes. When two nodes communicate, the receiving one measures the physical state, also called channel state information (CSI), which is normally a vector of real values. An entity called Agent Manager in the Fig. 2, estimates, measures and selects the appropriate values to be sent to the

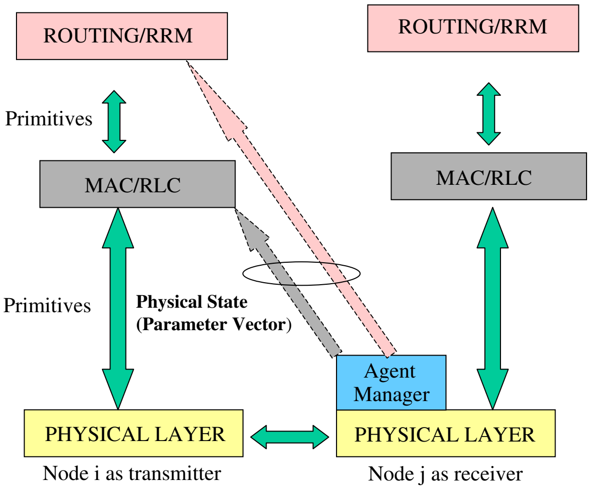


Fig. 2. Example of cross-layer interaction through an Agent Manager.

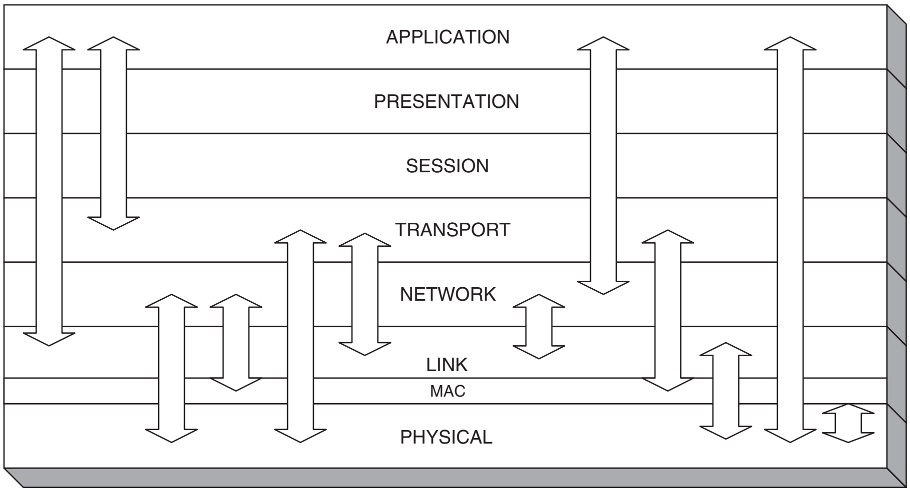


Fig. 1. Possible cross-layer communications.

upper layers of the transmitting node. These layers will actuate accordingly to adapt to the actual channel conditions, performing the cross-layer interaction. This Agent is the responsible of setting up and formatting the control information so that the cross-layer overload is minimized.

This example outlines a cross-layer interaction between two different nodes (namely transmitter and receiver), but it is worth to note that cross-layer design could also include the interaction between different layers of the same node of the communications system.

Finally, note that in each specific communications system, the suitability of the application of an certain cross-layer interaction should be carefully studied in order to assess that real system enhancements could be achieved.

The paper is organized as follows: Section 2 describes the state of the art about cross-layer issues, focusing on the RRM aspects that are covered by the other sections. Then, Section 3 addresses a tutorial description of the cross-layer design paradigms, trade-offs, control information issues, and it also outlines a classification of cross-layer mechanisms. Section 4 is devoted to the study in depth of the interaction between physical and MAC layers and its obtainable benefits. Specifically, three different representative scenarios are analysed and cross-layer mechanisms for them are introduced and described. Each subsection also shows numerical figures of the achieved gains. Finally, Section 5 is devoted to assess the conclusions.

2. State of the art

In recent years, research efforts focused on cross-layer design have been progressively increasing, leading to the huge amount of recent literature on the topic. Then, only some examples of each subsection of the research are cited.

Yeh and Cohen proposed a theoretical framework for cross-layer design [24] in the context of radio resource management (RRM) focusing on resource allocation algorithms. More recently, Yeh also developed this framework in [35]. Other tutorial-like very useful descriptions of the general cross-layer optimization paradigm have been also published [28–30].

Then, cross-layer research has been split into different fields of applications. Obviously, wireless communications are the most interesting research target for cross layering, due to the inherent variability of the radio channel and the potential enhancements that other layers can attain from knowing information about its state. Some research has been developed for general unspecific wireless systems, focusing specially on MAC issues [31,32,37,40], while others study in depth RRM issues as the optimal bandwidth allocation [43] or the optimal power assignment for this kind of systems [44,45,48]. Regarding specific types of networks or applications, for instance, ad hoc wireless networks have been an extensive field of cross-layer research [25,33,46,49] due to the totally wireless nature of the communications system. Also sensor networks, that represent an specific kind of ad hoc networks, have been a target for some cross-layer optimization developments [36,38,41]. Regarding wireless networks with infrastructure-based support, CDMA-based systems [39,42] and WLAN systems [26,34,47] have been also a extensive research target for cross-layer design, focusing also in specific applications as multimedia transmissions [26,42,43]. Some recent results of the authors about the specific interaction between the physical layer and the MAC are described in Section 4.

On the other hand, nowadays some R&D projects funded by the European Commission deal with the study of cross-layer interactions. Two IST STREP projects, the 4G MC-CDMA multiple-antenna system On chip for radio enhancements (4MORE, [57]) and the jointly optimising multimedia transmission in IP-based wireless networks (PHOENIX, [58]) address cross-layer issues.

The objective of 4MORE is to research, develop, integrate, and validate a cost effective, low power system on chip (SoC) solution for multi-antenna MC-CDMA mobile terminals, based on joint optimisation of layers 1 and 2 functions, whereas the aim of PHOENIX is to develop a scheme offering the possibility to let the application world (source coding, ciphering) and the transmission world (channel coding, modulation) to talk to each other over an IPv6 protocol stack (network world), so that they can jointly develop an end-to-end optimised wireless communication link.

There is also a project within an IST Network of Excellence, in particular the one named NewCom (network of excellence on wireless communications, [59]) that is focused on cross-layer optimizations. Some of the general concepts and ideas presented in this paper come from the first discussions within this project.

3. Cross-layer design

Several issues must be considered when undertaking cross-layer designs, being the additional signalling needed to extract relevant parameters from one layer that could be useful for other layers [23], a key issue. Then, the trade off between overhead and efficiency improvement should be analysed. Also, an appropriate logical channel, either common or dedicated, must be identified and reserved to transfer information between layer entities. In addition, different cross-layer architectures could be envisaged. Regarding the possible structures, we can basically divide them into two main categories:

- Each layer is modified according to the cross-layer interaction with the other layers. This means that some internal parameters of the protocol stack at each layer should be modified taking into account some information about the state of the other layers. For example, the structure of the MAC frame can be changed when it is known that a deep fading is present in the channel.
- An external entity manages the cross-layer interactions and defines the corresponding interfaces and primitives with each layer. We will call it cross-layer Manager. Fig. 3 shows the block structure of this kind of architecture.

In the next sub-sections, the different aspects of cross-layer design mentioned above are further developed in order to achieve a valuable gain in wireless systems.

3.1. Trade-off between cross-layer efficiency and overhead

When targeting cross-layer designs, normally a number of overheads turn up. For example, exploiting PHY layer will usually require certain overhead to transport the PHY layer information from entities such as smart antennas processing systems. Also training sequences may be needed for the accurate estimation of specific PHY layer state. Additional measurements at different layers may be required as well in order to extract location information to be exploited by a physical layer-aware routing algorithm. Besides, various methods for extraction, embedding and conveying reliability information (such as time-varying nature, predictability, confidence level, estimation accuracy, etc) along with the transmitted parameter set should be present and so on. Indeed, cross-layer information needs to be exchanged between entities in remote nodes by means of specific-purpose signalling channels.

In all the above cases, performance versus associated signalling trade-offs must be carefully

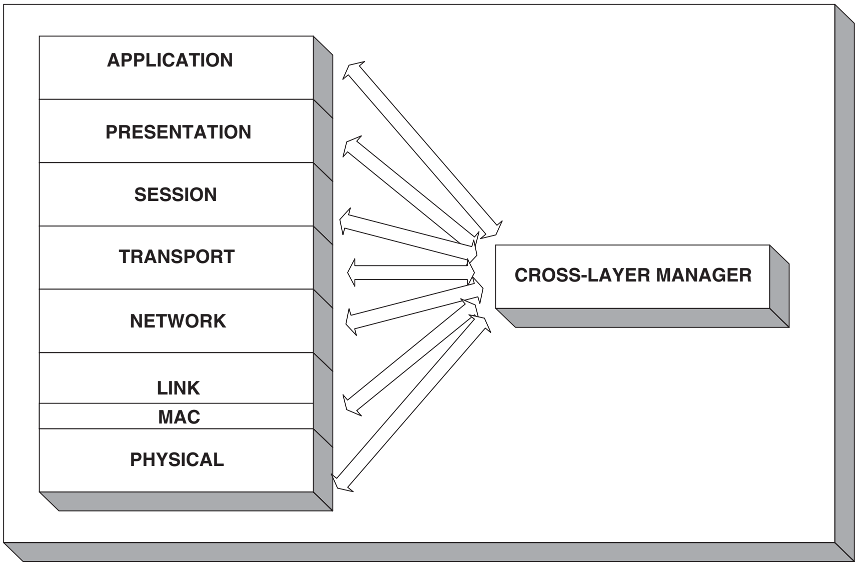


Fig. 3. Cross-layer design architecture.

analysed and assessed. As a result, the issues of information reliability and its partial knowledge at the end will arise as a consequence of noisy estimation procedures, quantization stages prior to mapping CSI into a feedback signalling channel, hardware limitations or, alternatively, as a result of transmission errors in the signalling channels, etc. In summary, the following issues should be addressed when tackling the trade-off in cross-layer optimization between control information and efficiency improvement:

- Number of entities and of layers involved in cross-layer information exchanges.
- Definition of the CSI proper information values useful for cross-layer adaptation.
- The associated increase in signalling load both for parameter extraction and transmission.
- The degree of robustness to channel errors.
- Timing and delay constraints, regarding the processing capacities of the involved entities.
- The resulting benefits in terms of system performance.

Taking into account this trade-off, we could distinguish four categories of cross-layer design that appear to be at the forefront of current research [55].

(1) The first category appears when considering the effects of one protocol layer on another. Certainly, better efficiencies can be attained making the interaction between relevant parameters of different layer protocols consistent. Then, this cross-layer interaction does not imply any communication between protocol layers at all. As an example of this category, we mention that it would be a waste of resources if the time-out period of a data-link layer is set to a higher value than that of any reliable layer above.

(2) The second category consists in an active effort by one protocol layer to deduce the state of other protocol layers by effectively looking "inside" packet headers or by making intelligent deductions from the traffic pattern of cross-layer design, unlike the layered approach currently applied. Then, this strategy does not involve transmission of additional information between layers. A representative case of this category [35] could be the prioritisation of transport-layer acknowledgment packets by the data-link layer, which has been shown to increase the performance of wireless schemes by reducing the number of time-outs at the transport layer. Also, this strategy reduces the number of re-transmissions, thus saving both wireless spectrum and energy. However, issues as the use of secure protocols which imply that headers from other layers are encrypted can constrain some of the advantages of this approach.

(3) The third category involves additional information that is being passed from one layer to another and bypasses protocol interfaces. Actual protocol structures are not modified. That is, the goal of this kind of cross-layer is to include the corresponding enhancement without modifying the structure neither the primitives of all the protocols in the protocol stack. Only extra information and processing is added into the normal primitive packets in order to react in each layer according to the variations in the other layers. An example of this approach could be a router that delivers packets out of the most appropriate wireless interface according to the state of the corresponding PHY layer (i.e. GPRS, UMTS, WLAN, etc.) [46].

(4) The fourth area of research is destined towards more long-term goals. It aims at modifying the protocols and their interfaces so that the most useful information is passed down and up between the layers, either as additional control signals, or encoded within the packet headers. As an example of this category, the MAC proposal described below in Section 4.2 has an embedded cross-layer interaction. This category includes the cross-layer classical concept as it has been generally understood up to date in the literature [22–27,29,30].

It is worth mentioning that unlike the fourth category described above, in the first category there is no additional overhead to the use of cross-layer techniques, whilst in the second and third categories no overhead is associated but an additional processing power could be required.

3.2. Definition of the control information for cross-layering

Having in mind the trade off mentioned in Section 3.1, the identification and selection of relevant cross-layer parameters to be exchanged among layers will depend on the functionalities being considered for cross-layer interaction and possibly on specific air interfaces and system concepts. However, a generic four-fold classification can be established for cross-layer information:

1. Channel state information (CSI) including estimates for channel impulse response, both in time and frequency domains, location information, vehicle/mobile speed, signal strength, interference level, interference modelling, condition number, etc.
2. QoS-related parameters, including delay, throughput, bit error rate (BER), packet error rate (PER) measurements, etc; for each one of the layers involved in the cross-layer interaction.
3. Resources made available in the corresponding node, such as multi-user reception capabilities, number and type of antennas, battery depletion level, etc.
4. Traffic pattern offered by each layer to the others. This includes data traffic information, knowledge of the data rate (constant or variable), data burstiness, data fragmentation, packet sizes, information about queue sizes, etc. In a multi-user environment, it could be needed to exchange this kind of information among different communications nodes.

Along with that, special care should be taken when assessing the algorithmic complexity in terms of realistic computational capabilities of existing hardware or its anticipated evolution. Computational capability can be vastly different for different types of user terminals (laptop, PDA, cell-phone, etc). Thus, some functionality above physical layer should be able to select the most appropriate scheme out the available ones.

3.3. Classification of cross-layer interactions

As mentioned in Section 1, there is a wide range of possible cross-layer interactions. Depending on the design aspect we focus on, it is possible to divide the cross-layer techniques into the following categories:

Regarding the entities performing cross layering:

- *Cross-layer inside a single node*: The different layers of the protocol stack inside a single node communicate and/or adapt to each other depending on the measures they perform or the information they exchange.
- *Cross-layer between remote nodes*: As pointed in Fig. 3, communicating nodes can exchange cross-layer information through a control channel so they can adapt their layers using measures or estimations done in the remote node.

Regarding the number of layers performing cross layering:

- *Two-layer interaction*: The simplest cross-layer approach involves only two layers that communicate with each other in order to optimise the transmission efficiency.
- *Multi-layer interaction*: Although no results have been published up to date regarding this possibility, the simultaneous interaction between more than two layers (for example, PHY, MAC and routing) can be investigated. Each layer can adapt taking into account the information received from all the other layers.

In principle, the cross-layer interaction can be envisaged concerning any of the layers of the OSI model, and the all the possibilities present potential benefits. However, regarding the type of layers performing cross layering, these interactions should be classified into two main categories:

- *Any layer interacting with PHY layer*: As PHY layer is the most time variant entity in a wireless communications system, any layer can adapt to the state of the channel. Physical state information can be sent to any layer (MAC, RLC, routing, application, etc.) in order to improve the system efficiency.
- *Upper layers' interaction*: When the PHY layer is not involved into the cross-layer interaction, a quite different scenario arises. This is due to the fact that the variability of the layers should probably appear as a consequence of an indirect influence with other system parameters or situations such as, among others, congestion, hardware failures, application variable QoS and so on.

Among all these possibilities, we are to describe in the rest of this paper three different MAC-PHY cross-layer interactions, including both remote nodes and a unique node, of the communications system, where the layers interchange explicit control information by means of specific control channels. For this purpose, representative scenarios and current standards for wireless personal communications systems are invoked. In order to get an insight of the obtainable benefits of this type of cross-layer interaction, some recent results will be shown to validate the benefits of exploiting cross-layer in wireless communications systems.

It is worth to mention that the final goal of cross-layer design is to improve the performance of end-to-end communications. Therefore, the proper consideration of applications and the source coding of the information to be transmitted should be also addressed in order to be suitable for systems which include cross-layer issues. Due to space constraints, this paper does not go inside this topic and focuses on the interaction between the lowest layers of the OSI model.

4. PHY–MAC cross-layer

As mentioned above, one of the most relevant areas in cross-layer optimisation is the interaction between PHY and MAC layers in wireless networks, as probably it is the most natural integration due to the proximity of the layers in the stack and the inherent variability of the channel state [24–49]. The independence of the channel state for different users in a multi-user environment arises the possibility of getting some overall improvement with the simple idea of selecting 'always the best possible transmission'. Obviously, the fairness in the final resource allocation should be considered for most applications in order to maintain a high per node performance.

Three kinds of results are presented in this section. Firstly, results for CDMA-based mobile communications systems, adopted in the current standard for 3G system like UMTS and CDMA2000 are described. Then, other results are shown for generic CDMA systems using a distributed MAC specially suited for cross-layer. This specific MAC protocol is presented and its advantages are highlighted. Finally, some results for WLAN systems are also shown, which are relevant as WLANs are currently the most representative wireless systems for medium range and low mobility scenarios.

4.1. CDMA downlink PHY–MAC interaction

In wideband CDMA systems such as UMTS (Universal Mobile Telecommunications System), advanced radio resource management (RRM) strategies are expected to play an outstanding role in the optimisation of air interface usage. In order to meet the QoS requirements of every user, scheduling algorithms within the UMTS RRM framework are able to assign radio resources in terms of transmission power (P_i) and data rate ($r_{\mathrm{b},i}$) on a frame-by-frame basis (10 ms, or multiples of this for UMTS) for every user i. In CDMA systems, assigning $r_{\mathrm{b},i}$ determines the required transmission power P_i since both magnitudes are coupled by means of the following expression [56]:

$$\frac{(P_i/L_{\mathrm{p},i})(W/r_{\mathrm{b},i})}{I+P_{\mathrm{N}}} \geqslant \left(\frac{E_{\mathrm{b}}}{N_0}\right)_i. \tag{1}$$

The left side of this inequality is the bit energy over power noise spectral density ratio (equivalent to the signal-to-noise ratio (SNR)) at the output of the CDMA receiver of user i. The numerator of this ratio is computed using $L_{\mathrm{p},i}$ which is the propagation loss between mobile i and its serving base station (the ratio P_i over $L_{\mathrm{p},i}$ represents the received power). The denominator is the total noise plus interference power, where I accounts for both the intracell and intercell interference and P_{N} is the noise power. Finally $(E_{\mathrm{b}}/N_o)_i$ is the bit energy over noise ratio that meets the required block error ratio (BLER) target for user i. Then, the actual bit energy over noise ratio must be always higher or equal to the target value.

Most of the scheduling policies proposed for CDMA-based systems rely exclusively on traffic considerations (traffic class, guaranteed rate, buffer size, etc.) to decide whether a user receives service or not and which transmission rate is allowed. Then, once a given $r_{\mathrm{b},i}$ is decided for user i, the transmission power P_i to be assigned can be derived from Eq. (1), taking into account averaged estimations of the propagation losses and interference levels. In this way, long-term variations in the radio channel are captured by the radio resource assignment in the computation of the allocated mean transmission power P_i. Furthermore, a fast power control mechanism is used in UMTS to follow the short-term variations of the radio channel and to update the transmission power accordingly. Usually scheduling policies provide fairness guarantees that are based mainly on traffic considerations and are irrespective of the conditions of the individual radio channel perceived for each user. Indeed, these channel conditions should also be considered in the scheduling process and it seems intuitive that such smart scheduling would lead to an efficiency improvement.

A cross-layer mechanism could be introduced using short-term information obtained from the fast power control mechanism to improve the scheduling strategy in a downlink channel. It is clear that the overall system efficiency could be enhanced if this information is used to prioritise those transmissions with better radio conditions (or whose conditions are getting better).

In the downlink of a WCDMA system, each base station has a certain total available transmission power, P_T, which has to be shared among the possible destination active users. Then, let us consider a UMTS downlink, where the fast power control mechanism keeps the transmission power $P_i(t)$ needed for user i to the minimum value to ensure the E_b/N_o required for each time t. The base station, using the power control commands coming from each user, adjusts this power dynamically. Furthermore, this power will fluctuate rapidly around a certain average value which depends on the slow varying radio channel conditions.

The cross-layer interaction will be performed between the MAC and the PHY layers at the base station, where the MAC receives from the PHY layer at the same node (base station) a CSI message that contains the value of $P_i(t)$ in every frame for each user. Then, it decides which users are enabled to transmit according to a prioritization function, trying to optimise the overall throughput. Fig. 4 shows an scheme of such cross-layer interaction. Regarding the classification described in Section 2, this is a single-node, two-layer, PHY–MAC cross-layer mechanism. Note that in this case it is not necessary to have an Agent Manager entity (see Fig. 2) as the cross-layer interaction is performed inside the base station.

The above-mentioned priority function should actually exploit the fluctuations of the channel conditions in a multi-user environment, assuming that they are independent among users. The transmissions will be scheduled in decreasing order of the value given by this function for each user. The rationale of this function is below explained. We impose the following characteristics for the priority function:

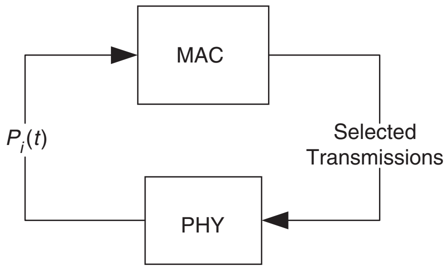


Fig. 4. Proposed cross-layer interaction.

- It should give a higher priority value to those users that have better channel conditions, that is, a lower $P_i(t)$.
- It should take into account the tendency of the channel variation. That is, setting higher priority to those users whose channel is getting better. This fact will maximize the probability that the required power for the actual transmission will be less than for users whose channel is getting worse.
- It should provide *fair* priority for all the users. That is, the priority function has to compensate, to some extent, those users having bad channel conditions along some consecutive frames, in order to reduce their transmission delay. There are some studies in the literature that address the fairness problem in RRM [27,39], so we should consider this matter with these ideas in mind.

Bearing in mind these ideas, it is clear that there are multiple possible priority functions that fulfil the described characteristics. Among them, we propose one, denoted as $\prod$, which has low computational complexity. The proposed priority function is:

$$\Pi = \beta\Gamma + (1-\beta)\Theta, \tag{2}$$

where Γ represents a value that should be proportional to the channel variation tendency in the last previous N frames (a higher value means that the channel is getting better, that is, the needed current transmission power is lower than the average one needed in the last N frames), whereas Θ is a value proportional to the expected future value of the required transmission power. Then β represents an adjustable parameter that allows weighting the influence on the priority function of the expected power value and its variation. The value for β will range from 0 to 1, where $\beta = 1$ means that we will be only considering the channel tendency, and $\beta = 0$ means that we will be only considering the power absolute expected values. Summarizing, the first term in $\prod$ takes into account the short-term tendency of the channel conditions, assigning a higher priority to those users whose channel is getting better, assuming that there will be a higher probability to need a lower transmission power in the next frame, whereas the second term takes into account directly the expected transmission power for the next frame (the future expected conditions). The parameter β allows a fine setting for specific scenarios.

It is worth to mention that the value of Θ should be normalized by the long-term average power for user *i*, in order to provide fairness in the priority assignment for users with different long-term needed power.

Therefore, with this priority function, the better is getting the channel for a user (i.e., the required power is decreasing) and the lower the estimated required power for a user in the next frame the higher its priority. In order to illustrate this reasoning, Fig. 5 shows a diagram with a channel variation for an example user and how the values of the terms in $\prod$ are read from the graphs to evaluate the priority value. Looking into these two terms of the priority function, Fig. 6 shows all the possible general situations where both of them can take different values depending on the channel variation and required transmission power (they are denoted as high, medium and low for the sake of simplicity, although they correspond to numerical values).

Finally, the value of $\prod$, which is associated to the fast power control evolution, will be used in the scheduling criteria to prioritise the transmission requests while considering their channel short-term variability. A reference of the obtainable gain for a reference scenario is described in the following. It is important to remark here that the prioritisation achieved by the value of $\prod$ may not be the only criterion used by the radio scheduler. Instead of this, it is expected to use this prioritisation combined with other criteria coming from traffic considerations such as service type, transmission buffer size, packet timeouts and the likes.

In order to get a reference of the obtainable gain using this cross-layer interaction, let us probe for reference values in a relevant scenario. Let us assume a scenario in which the total transmission power available for the downlink P_{T} is shared among M always-active users. Actually, the maximum number of users being served in each frame is limited by the condition that the sum of the individual power assignments must be less than the available power P_{T}. Then, in order to assess the capacity gain of incorporating a prioritisation criterion based on $\prod$, and assuming that there is no current scheduling reference for UMTS-like systems, we select a well-known round-robin (RR) strategy as a reference scheduler and assume that all the users are expected to be continuously served with the same "rights" attending to traffic considerations. Under such conditions, the RR scheduling algorithm will serve the users cyclically, while the proposed scheme will prioritise users exclusively on the basis of the function $\prod$. For the sake of simplicity, we have considered that all the users require the same bit rate $r_{\mathrm{b},i}$ and $\bar{P}_i$. Let us also assume a Rayleigh fading channel, where its coherence time (defined as the delay for getting an autocorrelation value about half the maximum one for zero delay) is inversely proportional to the user's speed, which will be constant. A lognormal shadowing is also present in the channel state. The other channel model details have been selected from [50].

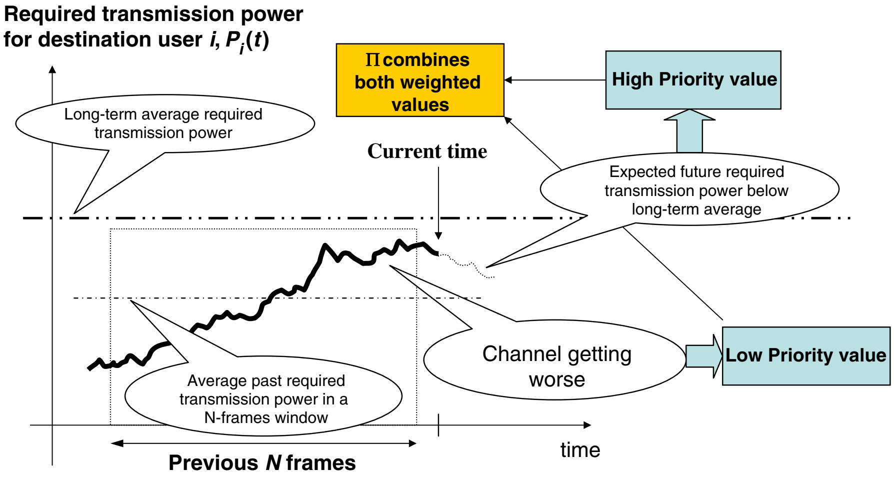
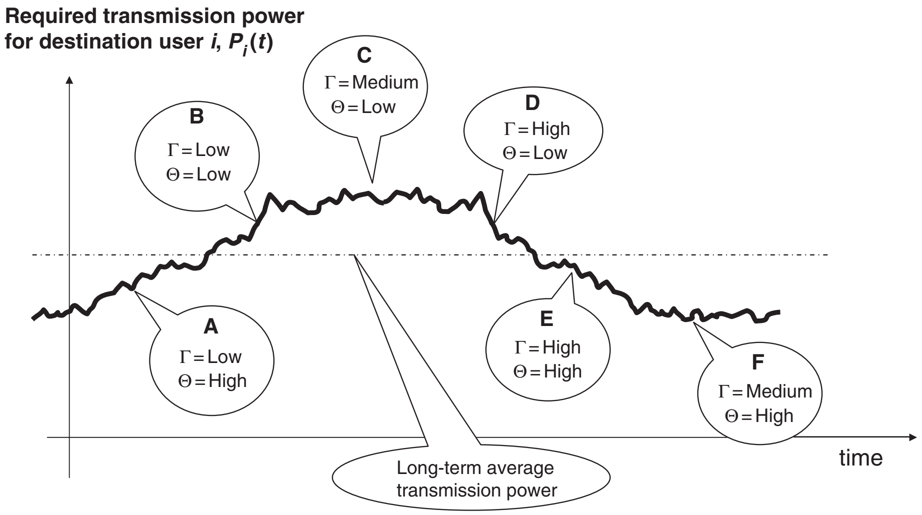


Fig. 5. Priority function definition.



A. Channel is getting worse but estimated required power is below the average
B. Channel is getting worse and estimated required power is above the average
C. Channel conditions are maintained and estimated required power is above the average
D. Channel is getting better but estimated required power is above the average
E. Channel is getting better and estimated required power is below the average
F. Channel conditions are maintained and estimated required power is above the average

Fig. 6. Priority function example cases.

Finally, the base station will estimate the future value for the transmission power as the last known (not estimated) value of the required transmission power, measured from the power control mechanism.

Based on the described scenario, numerical simulations have been performed in order to evaluate the gain obtained with the proposed mechanism. As stated above, we have used the RR strategy as a reference. Then, we define the gain obtained (in percentage) as the ratio between the increase of the average number of users that actually transmit in each frame (using the proposed algorithm) and the average number of users that transmit with the RR criterion. Calling $M_{\prod}$ the average number of users transmitting with the proposal, and M_{RR} the average number of users transmitting with the reference RR strategy, the gain G is calculated as

$$G(\%) = \frac{M_{\Pi} - M_{\mathrm{RR}}}{M_{\mathrm{RR}}} 100. \tag{3}$$

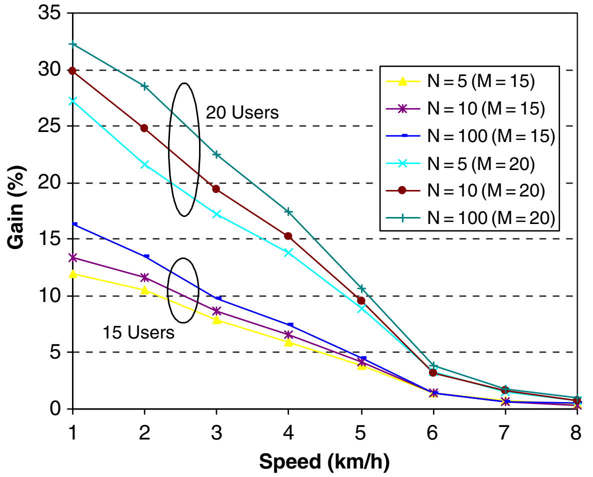


Fig. 7. Capacity gain of the proposed scheme versus a round-robin strategy when $\beta = 1$.

Firstly, and in order to get a figure of the gain that can be achieved with the proposed scheme, we consider the case of $\beta = 1$ in Π, which corresponds to the case where only the channel state variation is evaluated in the prioritization function. Fig. 7 shows the values of the gains obtained versus the mobile speed, when the total power available for the downlink is 10 times the average power needed for each user, that is $P_{\mathrm{T}} = 10 \times \bar{P}_i$. Various curves are shown for different number of users ($M = 15$ and 20) and values of N. The carrier frequency has been assumed to be 2 GHz.

As it is clearly shown, significant gains are achieved, up to more than 30% for a low mobility situation. The gain obtained increases with the number of users as the system takes more profit from the multi-user diversity. On the other hand, the gain decreases with the speed of the users, as the channel becomes more uncorrelated between consecutive frames. As a reference value, for the scenario conditions, notice that the channel coherence time (defined as the delay for getting an autocorrelation value about half the maximum one for zero delay) is about 10 ms (the frame time) when mobile's speed is 13 km/h. Then, for speed values approaching 13 km/h the channel is almost uncorrelated between two consecutive frames, and then the priority function $\prod$ reduces its usefulness. When mobility is low, $\prod$ captures the state of the channel seen by every user as well as its time variation, and the scheduling exploits this inherent multi-user diversity providing a significant capacity enhancement. Then, the proposed prioritization is especially useful for indoor or outdoor pedestrian environments.

Regarding the dependence on β, Fig. 8 shows the average delay, or equivalently, the average number of consecutive frames each user is unable to acquire a transmission opportunity, versus β. A speed of 1 km/h was selected, because the dependence on β is clearly accentuated at low speeds since channel conditions remain more stable. We can observe that the average transmission delay increases slightly with β, even this increase is negligible for large values of N. Then, it is shown that the specific selected value for β will not affect the performance of the mechanism.

Summarizing, this cross-layer technique makes data transmissions to be scheduled taking into account the power control information included in UMTS systems. While the channel state for each user is independent of the other users' channel, the proposal exploits the inherent multi-user diversity and provides a significant performance improvement using a smart and low-complexity priority function that takes into account the channel state and channel variation of each user.

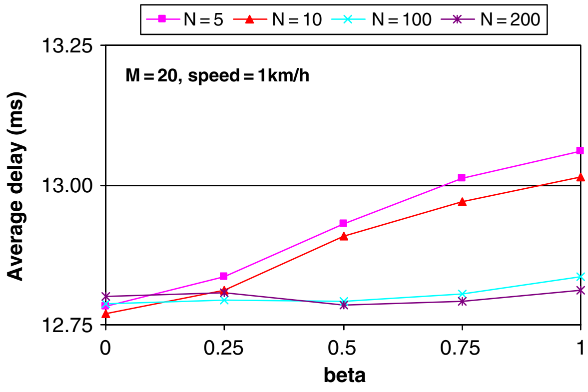


Fig. 8. Average access delay variation versus β.

4.2. *A distributed MAC protocol for cross-layering in a CDMA environment*

A great variety of medium access control (MAC) schemes have been developed and studied for wireless communication systems in the last years. Some of them are more fitted to applying cross-layer mechanisms than others. In particular, those whose architecture is based on queues are especially adequate to incorporate smart scheduling to the queues taking into account the channel state and its variation. Furthermore, not all the MAC protocols are equally suited for introducing cross-layer techniques without increasing the complexity of the system and the control information. Among the huge number of different MAC protocols proposed in the literature, we are to describe in detail one of them, which is a proposal of the authors, that fits remarkably into cross layering. The protocol is called Distributed Queuing Random Access Protocol (DQRAP/CDMA) when used in a CDMA environment [13,51], also called Distributed Queuing Collision Avoidance (DQCA) when used in a WLAN TDMA environment [52–53]. DQRAP/DQCA is a distributed always-stable high-performance protocol. It behaves as a random access mechanism for low traffic load and switches smoothly and automatically to a reservation scheme when traffic load grows, so the best of each mechanism is retained. Let us first describe the protocol operation so that its great characteristics could be shown. A more in depth explanation is in the Annex.

4.2.1. *MAC protocol description*

Without loss of generality, let us consider N data terminals which share a CDMA channel with K available spreading codes to communicate with a base station (the case of a TDMA channel is included for $K = 1$). The time axis is divided into frames, and each frame has two fields. The first field is the access field, which is further divided into m control minislots. The second field is the data part, where terminals will transmit their packets. We assume that every station has perfect frame and minislot synchronisation. The K spreading codes are put in order and we will denote K_i for the ith code. We consider that the terminals are able to change the spreading code for data and request transmission on a frame-by-frame basis. The messages generated by one terminal are split into frame-duration packets and put into a buffer. Each packet will be sent with the same spreading code but not all the packets pertaining to one message will necessarily be sent with the same spreading code.

The protocol uses two concatenated distributed queues: the collision resolution queue and the data transmission queue. When a message arrives at a given node, the corresponding terminal selects a spreading code following a certain set of rules (see Annex) and sends a request in one of the control mini-slots pertaining to this code. If it fails (i.e., the request collides with one or more requests from other messages), the node is notified so and it enters the collision resolution queue. Collisions are then resolved in the order fixed by the queue discipline, which can be whatever desired. In addition, the data transmission queue contains the messages that have succeeded in their request and are waiting to be transmitted to the base station also following the order fixed by the corresponding queue discipline. Collision resolution and data transmission processes work in parallel. Fig. 9 shows the queue model of the protocol operation. The elements in the queues are actually the transmitting nodes, firstly in the collision resolution queue while they access to the system, and then in the data transmission queue when they get a valid position in it.

All the terminals must have four integer counters, which represent the two logical distributed queues. It is worth to mention that these only four integers represent the whole operation and contents of both queues. We will denote them as TQ, RQ, pTQ and pRQ. TQ is the number of messages waiting for transmission in the distributed transmission queue. RQ is the number of collisions waiting for resolution in the distributed collision resolution queue. pTQ is the position of a given terminal in the data transmission queue and pRQ is the position of that terminal in the collision resolution queue. These values range from 0, meaning that the terminal does not have any position in the corresponding queue, to TQ or RQ (respectively). The value i indicates the ith position of the queue. TQ and RQ have the same value for all the terminals in the system (i.e., they represent *distributed* queues), while pTQ and pRQ have a specific value for each terminal. All four values are initially set to zero and must be kept updated using feedback information sent by the base station each frame, using a broadcast channel and following a set of rules described below. This control information consists of a ternary state data for each control mini-slot of every spreading code, and also has to include a final-message-bit for each code. The three different states that the base station must be able to distinguish are: empty (no access requests), success (only one access request) and collision. A collision will occur when more than one station transmits in the same mini-slot of the same spreading code. The final-message-bit is the mark that all the data terminals must send when they are transmitting the last packet from one message. This flag bit must be ON in the last packet of each message, and must be OFF in all the other packets. This mechanism allows all packets from a message to be transmitted with a single request. If messages are known to be short, it should be possible and convenient to switch off this mechanism and consider all messages formed by a single packet. It is worth mentioning that the control information that must be transmitted through the broadcast channel is very light, as only two bits per access mini-slot are enough to encode the needed information.

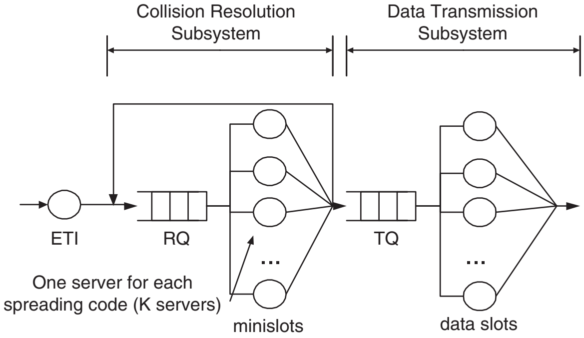


Fig. 9. DQRAP/CDMA queue model.

The protocol algorithm consists of three sets of rules that each data terminal has to follow at the end of each slot. They are, in order of execution, the queueing discipline rules (QDR), the data transmission rules (DTR) and the request transmission rules (RTR). The reader should also refer to [13] for a deeper comprehension of the MAC mechanism.

4.3. Cross-layer performance enhancement

DQRAP/DQCA is specially suited for including cross-layer design. On one hand, it has an embedded cross-layer interaction between MAC and PHY layers. Fig. 10 shows a simplified diagram of this interaction. Note that actually the cross-layer mechanism is performed between remote nodes. The receiver node detects the minislot access states and sends this information through the broadcast channel to the transmitter node. Then, and referring to the example shown in Fig. 2, it should exist an Agent Manager entity (not shown in Fig. 10 for simplicity) that sets the control information and sends it through the return control channel. The application of this MAC protocol with its inherent cross-layer mechanism optimises the transmissions and achieves a significant improvement in a CDMA uplink, both in terms of maximum throughput and average packet transmission delay, in comparison with an ALOHA-like or CSMA MAC scheme. Then, this mechanism is a remote, two-layer, PHY–MAC cross-layer (see Section 3.3).

On the other hand, as DQRAP/DQCA is based on distributed queues, the application of appropriate scheduling strategies in the queuing discipline rules taking into account cross-layer information may allow achieving an even higher significant improvement. The following additional cross-layer interaction has been proposed: in each frame, the MAC decides the optimum number of simultaneous transmissions and the optimum value of the transmission parameters in order to keep maximized the average effective transmitted bits per second as a function of the number of nodes in the transmission queue. When the number of users in the DTQ is low, the MAC knows that the interference level will be low and decides to use a low spreading factor, leading to higher data rates. On the contrary, if the number of users in DTQ is high, the MAC keeps bounded the maximum number of users (thus the interference level) and decides to use lower data rates. With this mechanism, it can be shown that the delay is kept at the minimum value for every transmission rate, and the maximum admissible traffic load is higher than in any other case. Indeed, as it is shown in Fig. 11, the application of this rate adaptation scheme keeps the average packet transmission delay with minimum values [53,54]. This figure compares the average packet transmission delay when considering a fixed transmission rate (basic MAC protocol) and a variable transmission rate optimised using the additional cross-layer information about the number of transmitting nodes in the DTQ of DQRAP/CDMA.

Furthermore, a significant energy saving can be achieved in the same system when considering the channel state information in the scheduling of the DTQ. The key idea is that the transmissions that require higher transmission power are delayed, then avoiding certain waste of energy and leading to an energy saving feature. An example of the achievable energy saving (in terms of average transmitted energy per packet) when using this scheduling, that is shown in Fig. 12. For further details in the scenario layout refer to [53,54]. This energy saving

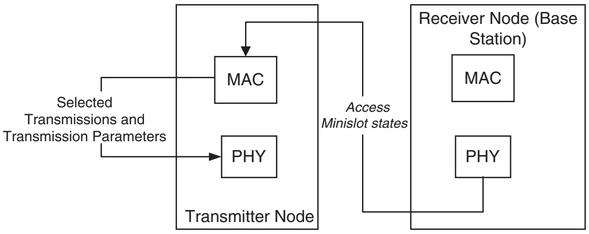


Fig. 10. DQCA cross-layer interaction.

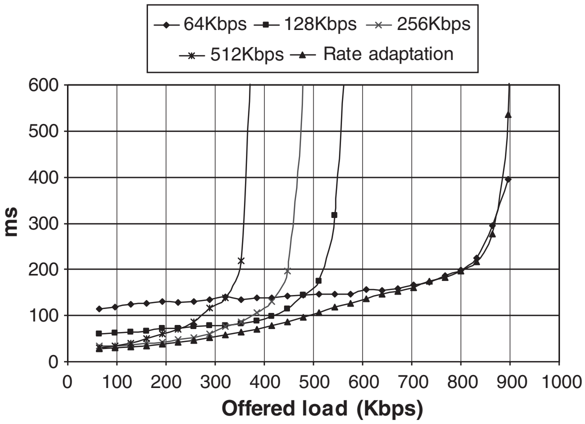


Fig. 11. Average packet delay considering different rate selection schemes using cross-layer information.

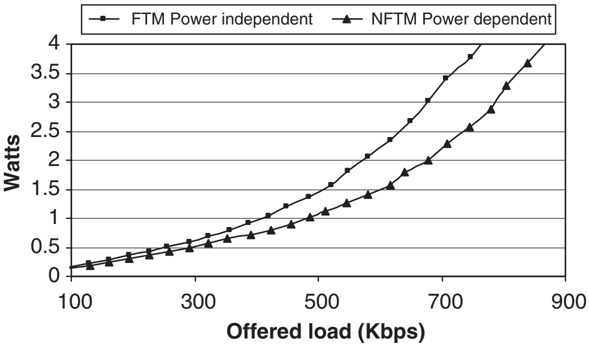


Fig. 12. Average packet transmission power when using cross-layer.

feature also reduces the interference level in the system, then it represents also an improvement in the overall system performance.

Summarizing, the cross-layer mechanisms create a different order of the queues taking into account the channel state information, obtaining an overall system improvement. Then, the achievable benefit of cross-layer is explicitly shown with the above significant results.

4.4. A distributed MAC protocol for cross layering in a WLAN environment

Focusing on the possibility of getting a certain throughput improvement in a WLAN environment using cross-layer techniques, let us consider the same DQCA MAC scheme applied to this kind of systems [52]. The MAC protocol itself has proven to provide a significant throughput improvement for certain scenario conditions [53] and it represents an inherent cross-layer mechanism. Note that even the Carrier Sense Multiple Access MAC protocol (used in the legacy IEEE 802.11 standard) could be considered a first approximation to cross layering as the MAC uses the PHY state indirectly. DQCA extends and improves the interaction between the MAC and the PHY layers as the former has to read the state of the m control mini-slots (detecting the three different states) of the latter. Notice that this is not a particular MAC primitive, thus becoming a cross-layer interaction.

From the analysis of the MAC of 802.11, it is clear that the throughput is remarkably degraded due to the presence of collisions and back-off periods. Then, the elimination of such wasted intervals should produce a throughput improvement [52,53]. The key feature of the proposed MAC scheme is that its distributed queues and embedded cross-layer mechanism eliminate the collisions and back-off periods in data packet transmissions. That DQRAP MAC scheme could provide this feature due to the availability in each terminal of the distributed queues this MAC enables. Then, any terminal would know precisely when to transmit and therefore the idle intervals present in the 802.11 could be avoided. Furthermore, this cross-layer dialogue the DQRAP MAC provides could be used to properly manage the MAC transmissions, in addition to determine the packet transmission time, and select the most appropriate PHY level data rate. In order to get a measure of the potential obtainable benefit of using this novel proposal, analytical results on maximum throughput have been obtained in a scenario where SNR variation is modelled by a two-state discrete Markov chain [52,53].

In order to show a figure of the obtainable gain when applying cross-layer techniques, let us suppose that we have a scenario with the characteristics summarized in Tables 1 and 2. The selected values are relevant for a general indoor (or at least low mobility) scenario, where cross-layer techniques become more relevant.

Then, a part from the inherent embedded cross-layer interaction of the DQRAP MAC, an additional cross-layer mechanism could be introduced on top of it in order to better exploit this technique. It consists in the reordering of the DQCA DTQ, taking into account the channel state of each user radio link. A virtual transmission queue is created. The order in this queue is different from the DTQ. The order of the virtual queue takes into account the channel state of each user, giving a higher position to those users having a higher measured SNR. The actual transmissions are carried out in the order defined in this virtual queue. In particular, the main decision of the MAC is to select which is the user that gets the first position in the virtual queue so it gets the grant to transmit in the following frame using the data rate according to its channel state. The user who gets the first position in DTQ will be the one which has the minimum value of pTQ according the protocol rules (see

Table 1
Scenario parameters

Number of users	10
Speed of users	1 km/h (channel coherence time 108 ms)
Channel *good* state probability	0.8 (SNR between 10 and 20 dB)
Channel *bad* state probability	0.2 (SNR between 0 and 10 dB)
Rate selection	Perfect following thresholds in Table 2
Traffic generation	Poisson
Packet size (L)	Variable

Table 2
Data rate thresholds

Rate	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
SNR (dB)	<4	4–7.5	7.5–11	>11

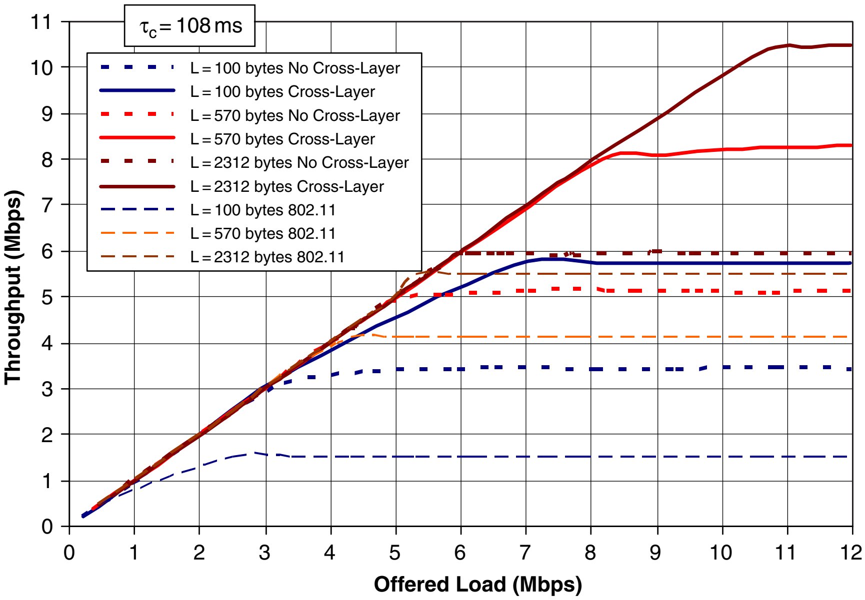


Fig. 13. Obtainable gain in terms of throughput when applying cross-layer techniques.

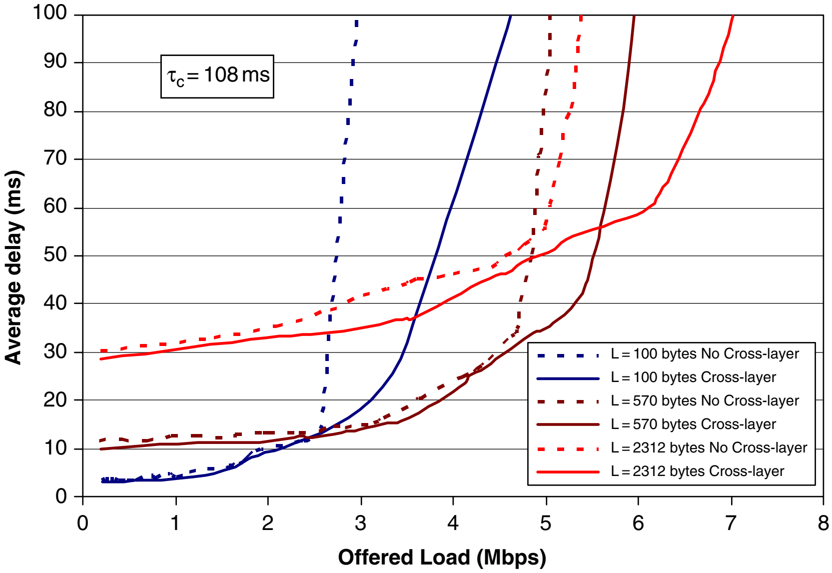


Fig. 14. Obtainable gain in terms of transmission delay when applying cross-layer techniques.

Section 4.2) among those with the better channel conditions (i.e. the higher SNR threshold). Then, we propose to have a transmitting user with the faster rate from the available ones. This technique optimises the channel overall efficiency.

With these conditions, Figs. 13 and 14 show, respectively, the comparison of the throughput and transmission delay when using this cross-layer technique with respect to the case of the legacy MAC procedure. The reference throughput value for a system using 802.11 is also plotted in Fig. 13, showing the potential benefits provided by these proposals, both in terms of delay and throughput.

It can be shown that a significant throughput gain can be obtained (up to 77% for packets of 2312 bytes) when applying the deeper cross-layer mechanism, and even the legacy protocol, which has an inherent cross-layer assumption, provides a relevant enhancement. Furthermore, as the channel is used more efficiently, the average packet transmission delay is also slightly reduced. Even more, if can be shown that this improvement is achieved without paying any cost in the fairness of the transmissions, as the variance of the packet delay is not increased. Obviously, this is true if the channel variation of each users is independent from the channel variation of the other users. In short, the key idea of this enhancement is that the MAC protocol and the cross-layer mechanism almost eliminate the wasted inactive periods of the legacy standard. The CSI information read from the PHY layer by the MAC leads the algorithm to conveniently order the transmissions, optimizing the channel efficiency while selecting the best transmission option among the available set. This is performed due to the smart scheduling that creates a virtual queue whose ordering depends on the channel conditions, that is, the nodes with better channel conditions are 'pushed' to the top of the queue.

Then, this example clearly shows the vast field of exploration of the enhancements that can arise from the use of cross layering in wireless communications systems.

5. Conclusions

Cross-layer techniques where different layers of wireless communications systems interchange control information in order to optimise the use of the scarce radio resources are a wide relatively unexplored research area where huge potential benefits can be achieved. The interaction between PHY and MAC layers has been the first explored issue in this area and it has shown a first set of possible enhancements. For example, while the channel state in a multi-user environment is independent for each one of the users, cross layering can exploit the inherent multi-user diversity and provide a significant performance improvement. Average transmission delay reduction, energy saving and QoS features are only a few of the possible achievable benefits. This paper has outlined some examples of the recent results in this research area for several representative scenarios and then it foresees the importance of keeping investing efforts in this direction so higher enhancements can be arisen.

Acknowledgments

The authors want to highly appreciate the support provided by COSMOS project, which is funded by Spanish CICYT (Ref. TEC2004-00518).

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