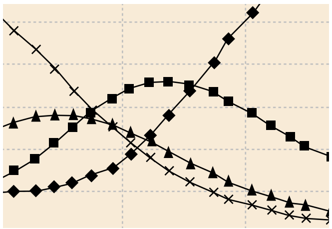

Automatic Rate Adaptation and Energy-Saving Mechanisms Based on Cross-Layer Information for Packet-Switched Data Networks

LUIS ALONSO AND RAMON AGUSTI
POLYTECHNIC UNIVERSITY OF CATALONIA (UPC)

Abstract

A set of novel PHY-MAC mechanisms based on a cross-layer dialogue have been proposed, and their performance has been analyzed. System efficiency improvement is achieved by means of automatic transmission rate adaptation, trading off bit rate for power, with resulting energy saving features in a generic packet-switched CDMA access network. The rate adaptation mechanism improves spectrum efficiency while keeping packet delay minimized. On the other hand, power-dependent strategies reduce power consumption and intercell interference. Simulation results show that the benefits obtained are very encouraging, so the proposed schemes could be used in future communication systems.

Introduction

Current research activities in the field of wireless mobile communications are focused on evolving new standards in the framework of so-called fourth-generation (4G) systems. These systems include networks with multimode, multiband, and multimedia high-capacity mobile terminals. Indeed, such future systems should be able to fulfill a set of stringent requirements for quality of service (QoS), mainly in terms of throughput, delay and error rate.

Moreover, considerable research efforts have been put into improving the spectral efficiency of individual wireless links. On one hand, at the physical layer (PHY) level, advanced signal processing techniques have been devised to face problems such as noise, interference, and unwanted signal replicas caused by the random and time-varying nature of radio channels.

On the other hand, a great variety of medium access control (MAC) schemes have been developed for these scenarios. In particular, two innovative aspects have been taken into account when designing these MAC protocols: the packet-switched nature of multimedia communications and the need to fulfill service-dependent QoS requirements.

However, advances attained in either the PHY or MAC layer have barely taken into account those achieved in the other layer; actually, they have widely ignored each other. It seems clear that system performance improvements could arise from some communication between these layers.

Several issues must be considered when undertaking cross-layer designs. First of all, additional signaling is needed to extract relevant parameters from the PHY layer that could be useful for MAC algorithms. Also, an appropriate logical channel, either common or dedicated, must be identified and reserved to transfer PHY information to upper-layer entities. Additionally, in wireless networks MAC algorithms should be decentralized to minimize control overhead.

In addition, cellular and ad hoc networks must properly manage power consumption in radio transmission, with the objectives of interference limitation and energy saving. Interference limitation is critical for code-division multiple access (CDMA) systems since spectrum efficiency depends on it. Energy saving is relevant when the nodes are battery-dependent. Some research has addressed improving power management, proposing strategies based on modifying different layers of the communications system and showing that adapting transmission to channel fading significantly improves link efficiency [1]. Others adapt the radio transmission parameters (frame length, error control, equalization, etc.) to minimize power consumption for varying channel conditions [2]. The source coding itself can save power and reduce interference levels in CDMA systems [3]. In cellular systems one may also use efficient base station assignment to save energy [4]. In addition, MAC protocols with a low-power-consuming state, called a **doze** state, enable energy saving when mobile nodes do not need to send data [5]. Other novel automatic repeat request (ARQ) schemes reduce the number of control packets and then decrease the number of unnecessary transmissions for energy savings [6]. Discontinuous reception also saves energy, periodically and randomly powering off the nodes [7]. Furthermore, discontinuous (pulsed) transmission in idle periods achieves some charge recovery in electrochemical batteries, leading to energy-efficient transmission strategies [8]. These mechanisms tackle a trade-off between energy saving and packet delay (QoS).

With all these ideas in mind, this article describes wireless communications where the MAC layer is aware of the current channel state of all nodes in the system and uses this information to save power, improving system performance via an adaptive distributed MAC protocol [9]. The PHY layer derives the optimal number of simultaneous communications to be handled. This number and the channel state for links between every node and a central base station are known to the MAC layer, which enlarges or shrinks the number of simultaneous users allowed in each frame.

In CDMA the binary transmission rate is modified simply by changing the spreading factor of each transmission. This MAC algorithm accurately estimates the traffic load in each frame. Therefore, distributed rate adaptation through spreading factor selection uses both the traffic information provided by the MAC and the channel state estimate from the PHY

This research was supported by CYCIT project TI2001-2222

Frame duration	10 ms
Maximum spreading factor	64
Minimum spreading factor	8
Maximum data rate	480 kb/s
Minimum data rate	60 kb/s
Number of mobile nodes	100
Mean generated packet size	1000 bits
Maximum number of simultaneous transmissions	17
Number of slots in control subframe	3
Access request sequence length	256 chips
Design access detection probability	0.95
Design access detection false alarm probability	10^{-3}

TABLE 1. *Main parameter values.*

layer, which is a cross-layer concept. Moreover, the algorithm's energy saving features improve battery life and reduce intercell interference. Simulations quantify the benefits of the proposed techniques.

The article is organized as follows. We first describe the use case scenario. We then describe the novel mechanisms and explain simulation results using the use case scenario. We address both rate adaptation and energy saving features. Finally, we conclude the article.

Scenario

Consider a cellular system where a certain number of mobile nodes share a common packet-switched channel to communicate with a base station. Since the distributed nature of the MAC scheme is most relevant to the uplink, the analysis focuses on this link. The analysis is also applicable to the downlink. The CDMA access method has a slotted time axis, so transmissions are allowed to start only in specific instants.

MAC Layer

The MAC protocol considered is DQRAP/CDMA [9], which 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. For brevity, only an overview of the protocol is included here.

This MAC protocol is based on two distributed queues. The data transmission queue (DTQ) is devoted to data packet transmission scheduling, while the collision resolution queue (CRQ) is devoted to the collision resolution algorithm.

These two queues are represented by four integers maintained by each node, updated each frame via simple feedback broadcast by the base station through a reserved downlink control channel. These four numbers are denoted TQ, RQ, pTQ, and pRQ. TQ is the number of messages waiting in the DTQ. RQ is the number of collisions waiting for resolution in the CRQ. pTQ is the node position in the DTQ (where pTQ = 0 means that the node is out of DTQ). And pRQ is the node position within the CRQ (where pRQ = 0 also means that the node is out of CRQ).

TQ and RQ have the same values for all nodes (i.e., they represent *distributed* queues), while pTQ and pRQ may differ from node to node as they denote the positions within the queues of each node.

A short time interval (subframe) is reserved for access attempts in each frame, and some control slots are defined within this subframe. The basic idea of the MAC protocol is to concentrate user accesses and collisions in this reserved control interval while the rest of the frame is devoted to collision-free data transmission. For each one of the control slots, the base station must detect one of three possible states:

- No transmission has been made during the control slot.
- Only one access request has been transmitted.
- More than one access request has been transmitted (collision).

Then the base station must broadcast the state of all the control slots (less than 2 b/slot); with this information all nodes will update their distributed queues, applying a certain defined set of rules [9].

The maximum number of simultaneous access requests and data transmissions is defined as M. The number of spreading codes necessary in the system is also M. These codes are arbitrarily ordered in a list. K_i is the ith code within this list.

A node arriving in the system with data to transmit checks the state of both the distributed queues to decide whether it is enabled to attempt a system access or data transmission. Users are forbidden from attempting accesses if the number of collisions pending resolution is greater than or equal to M. This key feature of the protocol avoids unstable situations. If the user is allowed access, it selects one of the available spreading codes applying some rules defined by the protocol. Then it randomly selects one of the control slots of the control subframe and transmits an access request using the selected spreading code.

After an access request transmission, two situations are possible:

- No other node has transmitted an access request at the same moment and using the same spreading code. In this case the access request will be successful, and the accessing node will enter the DTQ, getting a valid value for its pTQ (pTQ > 0). In this queue it will wait for its turn to transmit a data packet and will be inhibited from sending new access requests.
- One or more other nodes have transmitted access requests at the same time and using the same spreading code. In this case the access request will collide, and the node will enter the CRQ, getting a valid value for its pRQ (pRQ > 0). In the CRQ it will wait for its turn to transmit a new access request in order to resolve the collision.

Furthermore, ALOHA-like data access transmission is allowed when the number of nodes in DTQ is lower than M, letting nodes transmit using the first free code when TQ < M.

The MAC protocol algorithm is formally defined by a set of rules each user follows at the end of every frame. Furthermore, the access request detection scheme is not ideal, with detection and false alarm probabilities taken into account as described in [9].

Other Parameters

Mobile nodes are modeled as Poisson traffic patterns with variable arrival rate and exponentially distributed packet sizes. The number of bits transmitted in each frame depends on the spreading factor.

At the link level, error detection is included in data transmissions, so packets with errors are detected, initiating a Stop&Wait ARQ sequence.

Table 1 shows the values of the parameters when obtaining the results presented in the following sections.

Cross-Layer Dialogue

The objective is to use cross-layer information to enhance the MAC mechanism. There are at least two possible ways of tackling cross-layer MAC adaptation, depending on the DTQ policy:

- Fix the DTQ packet position in the transmission order. This is first in first out (FIFO) transmission management (FTM).
- Allow the packets of the DTQ to be sent out of order. Suppose DTQ contains three packets. The third packet on the queue could be transmitted first. This option is non-FIFO transmission management (NFTM).

FIFO Transmission Management

Following the cross-layer philosophy, assume that the MAC protocol is aware of the channel state of the links between the nodes that own a packet in the DTQ and the base station. This information consists of a real vector that contains the channel attenuation for each of the links. This information is broadcast by the base station to all the mobile nodes. Among the functions of the MAC layer, we will focus on two main objectives:
- Maximize the throughput.
- Minimize the transmission power used by all nodes.

With these objectives, the MAC layer selects the number of simultaneous transmissions and spreading factor accordingly. At least two possibilities are described below:
- The power-independent algorithm
- The power-dependent algorithm

The FTM Power-Independent Algorithm — As a first step, focus on maximizing throughput. To simplify the CDMA channel, we use the Gaussian hypothesis [10] for intracell interference, neglect the thermal noise and intercell interference effect, and assume that all nodes use the same spreading factor and adjust transmission power by means of a separate control channel for the same received power. In this situation, the bit error probability can be evaluated as

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{S_f}{M-1}}\right), \tag{1}$$

where S_f is the used spreading factor and M is the number of simultaneous transmissions. Other expressions for Eq. 1 may be feasible according to the receiver. Let K be the number of simultaneous packet transmissions (i.e., $M = K$) the system accepts to get the desired P_b using the highest S_f. This value is determined by the receiver PHY layer and sent to the transmitter MAC layer (cross-layer information) through a reserved error-free control channel.

If the number of packets in DTQ (i.e., TQ) is lower than K, it is possible to reduce S_f to maximize the number of bits transmitted, increasing the transmission rate without degrading the quality of transmissions. Since the spreading factor is usually a power of 2, the rate adaptation algorithm is as follows.

For each frame, the MAC checks the value of TQ and acts according to the following rules (distributed algorithm):
- If TQ > K, the number of simultaneous packet transmissions will be K, and all of them will be performed using the maximum spreading factor, S_f. All the packets in the queue beyond the Kth position will be backed off. The nodes owning the Kth first packets in DTQ will transmit them using the maximum spreading factor, S_f.
- If $(K/2^n) \geq$ TQ > $(K/2^{(n+1)})$, where n is an integer value, the number of simultaneous packet transmissions will be TQ, and all of them will be performed using spreading factor $S_f/2^n$. Obviously, the resulting spreading factor will never be lower than the minimum allowed in the system.

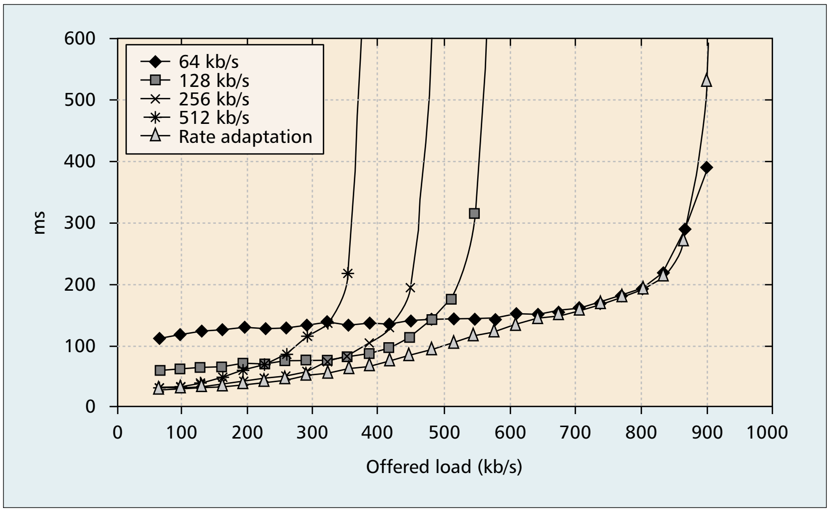

FIGURE 1. *Average packet delay considering different rate selection schemes (FTM power-independent).*

In any case, the value of n will be upper bounded by the minimum spreading factor available in the system.

The FTM Power-Dependent Algorithm — The FTM power-dependent algorithm considers the information about the attenuations of the different links between mobiles and the base station. The objective is to adapt M, the number of simultaneous transmissions, to keep the intercell interference level constant while reducing it as well.

$\boldsymbol{L}$ is the channel state information vector (real valued) and $L(i)$ is the normalized channel attenuation for the ith packet in the DTQ. The normalization makes $L(i) = 1$ correspond to the minimum channel attenuation.

For initial analysis, assume that all the mobile nodes have the same E_b/N_0 target and the intercell interference (from other cells) is constant. Then the transmission power of each node will be increased accordingly to its channel attenuation. Indeed, if a node has a packet in the ith position of TQ, its transmission power (P_{TXi}) in an interference limited system will be:

$$P_{TXi} = k \cdot L(i) \tag{2}$$

where k is a constant that depends on all the physical parameters (antennas gain, frequency dependency, etc.) and the required E_b/N_0.

The reasoning is as follows: If $L(i) > 2$, the ith packet in DTQ will be transmitted with at least twice the minimum possible transmission power. Then its interference impact in the whole system (other cells) is equivalent to two packets sent with minimum power, so K should be reduced accordingly to maintain the intercell interference level. The modifications to K are generalizations of this idea.

The outline of the algorithm is:
1) Execute the FTM power-independent algorithm.
2) Let K be the number of simultaneous transmissions obtained from point 1 (previous point). Consider the first value of L, $L(1)$.
3) If $2^{n-1} \leq L(1) < 2^n$, set K to $K - n$.
4) Consider the next value of $\boldsymbol{L}$, $L(i)$.
- If $i > K$, the algorithm ends and the final value for K is the current one.
- If $i \leq K$, follow the previous rule.
5) Return to point 4 until the algorithm finishes.

In this power-dependent case, the number of maximum transmissions is low, so the maximum throughput in steady-state is lower than in the independent case, keeping the maximum transmission power bounded. If DTQ uses FIFO, the way to keep the total transmit power bounded is to limit the number of simultaneous transmissions and then reduce the throughput. A non-FIFO strategy for managing the transmission queue (DTQ) could overcome this limitation, improving the system throughput while keeping the average transmitted power in low values, thus reducing intercell interference and saving power at the nodes. The next section analyses this option.

The NFTM Power-Dependent Algorithm

If we admit that the transmission order could be different from the queue order of the packets, a more flexible scenario arises. Consider the following example: Suppose the DTQ has four packets, and that $L(1) = L(2) = 10$ and $L(3) = L(4) = 1$. Suppose the optimum number of simultaneous transmissions is $K = 2$. In this situation, it would be better for overall system performance to transmit the third and fourth packets with the minimum transmit power instead of transmitting the first and second ones with 10 times more power needed. That is, the queue order does not guarantee the minimum transmission power and thus the minimum intercell interference level produced to other cells.

Therefore, as we are considering a packet-switched network, an automatic algorithm that makes an appropriate decision for each system situation could be envisaged. The way to do this is based on a virtual data transmission queue (VDTQ). The packets in a VDTQ will be the same that belong to a DTQ, but their order will be changed according to a virtual priority (VP_i) value calculated for each packet. This value is calculated based on its position in DTQ (pTQ_i) and the channel state information (attenuation) corresponding to the node that owns the packet ($L(i)$). Packets in VDTQ will be ordered using their VP, and the actual transmission order will be the one in this queue. In general, VP_i must be any monotonous increasing function $g(pTQ_i, L(i))$ with both pTQ_i and $L(i)$.

The key is to prioritize packet transmissions considering their age, measured as their position in the data transmission queue, and the channel state for the node that has to perform the transmission. The idea is to defer the transmissions that need high transmission power, and allow the nodes with a good channel state to transmit first so that they can advantage of their better position to save energy. The proper selection of the generation function ($g(x,y)$) allows weighting of the contribution of each parameter (pTQ and $L(i)$) in the prioritization.

In particular, to illustrate the potential benefits of this mechanism, a function $g(x,y)$ is selected. The results later use the following expression to calculate VP_i:

$$VP_i = pTQ_i \cdot L(i). \qquad (3)$$

With this expression, data packets are sent in an order that considers both their age and the channel state information with the same multiplicative weight. Simulations presented later show the benefits of this mechanism in terms of both energy saving and interference reduction at the expense of a small mean delay increase.

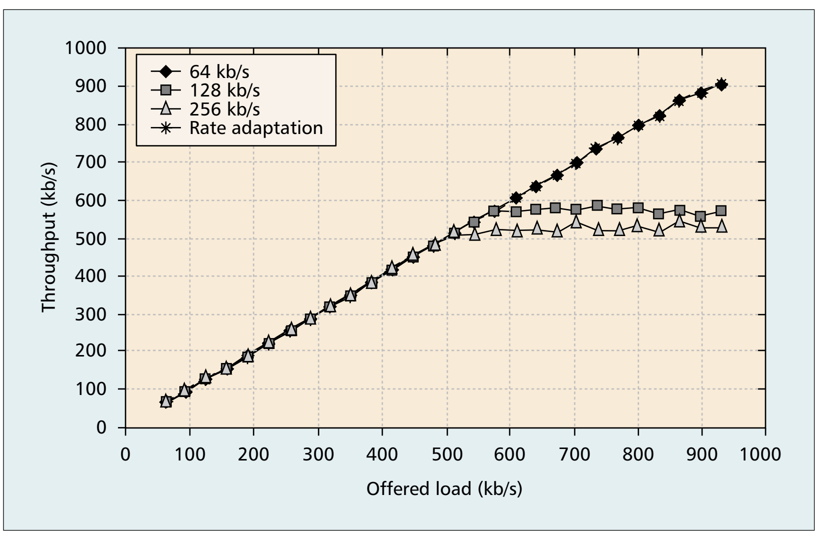

FIGURE 2. *Comparative throughput (FTM power-independent).*

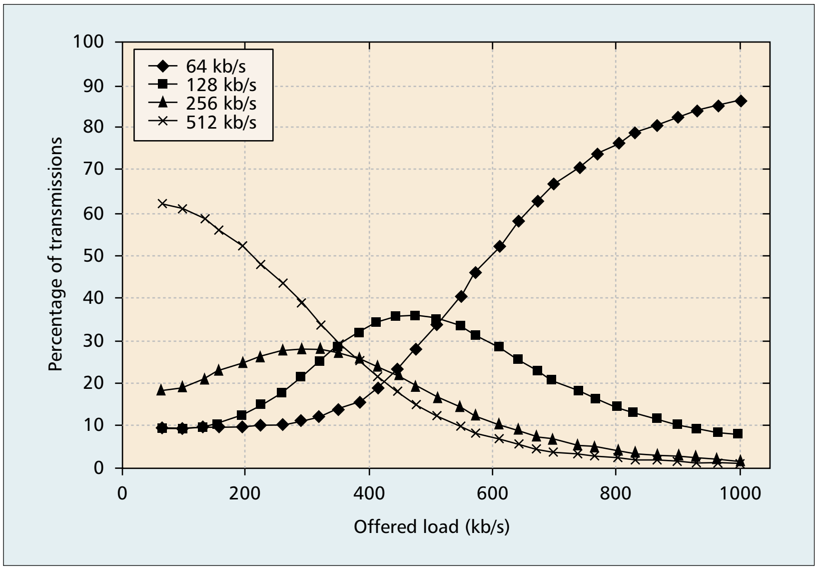

FIGURE 3. *Distribution of transmission rates (FTM power-independent).*

Simulation Results

The cross-layer-based ideas mentioned earlier have been tested by simulations, and the results obtained are shown in this section following the ideas outlined earlier.

FTM Results

The FTM Power-Independent Algorithm — The simulations of Fig. 1 show the mean packet delay for a system using four different transmission rates corresponding to four different spreading factors. Data rates range from 64 kb/s to 512 kb/s per node, which corresponds to spreading factors from 64 to 8, respectively.

Five curves are shown in this figure. The ones pointed with a specific rate are based on the assumption that all the nodes always transmit with a fixed spreading factor. The curve called *rate adaptation* is the case using the FTM power-independent algorithm where the rate used in each frame is changed as a function of the instantaneous traffic load. When using the rate adaptation scheme, the mean packet delay is always kept at the minimum value of any of the fixed rate schemes. Moreover, the delay curve follows the envelope of all the fixed rate curves, always selecting the best choice for the offered traffic load in the system. Furthermore, the maximum supported traffic load with bounded delay is always higher when using the rate adaptation mechanism than when considering any one of the fixed rates.

On the other hand, Fig. 2 shows the throughput (measured in terms of correctly transmitted bits per second) for the same scenario. The rate adaptation algorithm always keeps the maximum possible throughput in the system, that with the maximum allowed spreading factor. This shows that the gain obtained in delay by the rate adaptation mechanism does not produce any loss in throughput.

Going into further detail, Fig. 3 shows the distribution of the selected rates (in percentage) for each packet transmission as a function of the offered traffic load. This value is calculated as the ratio between the number of packets sent with a specific spreading factor and the total number of transmitted packets. The highest rate is used to a greater extent when the traffic load is low, taking advantage of the low interference level and allowing more bits to be sent in the same frame. When traffic load becomes heavy, lower rates are used in order to maintain the quality of the transmissions. These results verify the correct functioning of the proposal. We can conclude that the proposed rate adaptation scheme is an appropriate strategy to improve the spectral efficiency of the system.

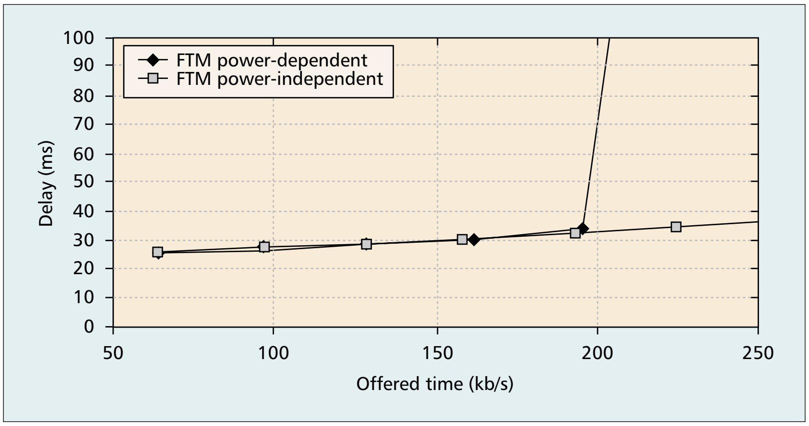

FIGURE 4. *Comparative average packet delay.*

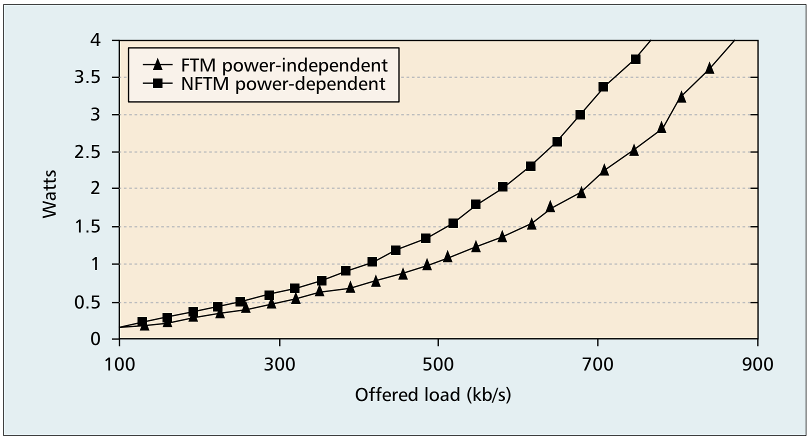

FIGURE 5. *Average packet transmission power.*

FTM Power-Dependent Algorithm Result**s** — Now consider the second objective of an earlier section, maintaining intercell interference for given channel conditions. We modify the MAC-PHY collaboration to reduce the transmission power, pursuing both interference management and energy saving objectives. The simulated scenario is the one described earlier. The nodes are uniformly distributed throughout the studied location and move at constant speed (uniformly distributed random direction) of 90 km/h (25 m/s). The base station is located in the center of the studied area. The channel attenuation follows a lognormal distribution shadowing effect with a correlation distance of 20 m. That is, the shadowing random variable for a mobile node is generated each time it has moved 20 m. The standard deviation of the lognormal shadowing is 8 dB. On the other hand, we consider that the channel state information vector $\boldsymbol{L}$ is broadcast by the base station twice per second in order to allow the mobile nodes to update all their VP_i values. In this case, Fig. 4 shows the mean packet delay of the system, comparing the power-dependent and power-independent strategies.

The mean packet delay is kept the same as for the power-independent case until the traffic load exceeds a threshold. In the power-dependent case, the number of maximum transmissions is kept in low values, and therefore the maximum allowable traffic load in steady state is lower than in the power-independent case. Indeed, this fact keeps the maximum transmit power bounded. As the maximum throughput is kept under a certain bound, the interference level produced to other cells is also kept bounded. The DTQ is managed with a FIFO criteria, so the unique way to lower the transmit power is to limit the number of simultaneous transmissions. Therefore, the interference limitation and power saving is obtained paying a cost in terms of maximum throughput. The next section analyzes the non-FIFO scheduling of transmissions in order to overcome this limitation.

NFTM Power-Dependent Algorithm Results

Maintaining the set of parameters for the scenario (from previous points), and using the novel scheduling criteria presented earlier, a set of computer simulations characterize NFTM power-dependent algorithm performance. Figure 5 shows the average packet transmission power compared to the FTM power-independent option, showing the energy saved. This energy saving also implies a reduction in the interference level produced in other neighboring cells. These results are obtained assuming that the intercell interference level received in the studied cell is unresponsive (i.e., constant). In a cellular system with ideal power control, a reduction in the average transmission power in a certain cell will reduce the intercell interference produced to neighboring cells Then, the transmission power of mobiles in the cells will be also reduced, and therefore the intercell interference level received at the studied cell will also decrease. For simplicity, this feedback effect has not been taken into account, so the transmission power reduction presented in Fig. 5 is really a lower bound (pessimistic bound) of the achievable energy saving. This assumption used in the literature is called the stationary, unresponsive interference scenario [11].

The difference in transmitted power increases as the offered load increases. This shows that the proposed mechanism is acting more aggressively when the transmission queue is nearly full, conveniently ordering the transmissions to reduce the transmitted power, and thus the intercell interference and power consumption. Actually, this mechanism takes advantage of managing multiple CDMA channels instead of a single high-capacity channel by selecting in each frame the best set of channels to reduce power consumption and interference. Moreover, Fig. 6 shows that the mean packet delay for both FTM power-independent and NFTM power-dependent strategies are very close, and the difference gets shorter when traffic load increases, that is, when the proposed mechanism is acting more efficiently.

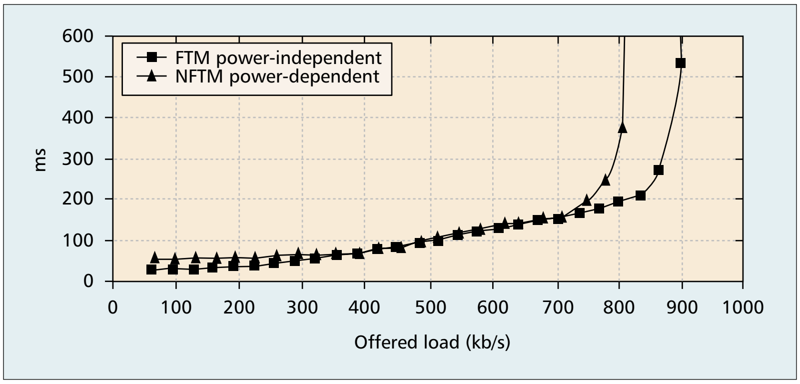

FIGURE 6. *Average packet delay.*

For all traffic situations, the number of simultaneous transmissions is adjusted to maintain the intracell interference and reduce the intercell interference. Therefore, some packet transmissions are deferred, and the maximum stable throughput is slightly reduced. However, the energy saving feature is obtained only by paying a very low delay and throughput cost, which is a key feature compared to other schemes [1–8].

We can conclude that this new proposed scheme is able to reduce the overall intercell interference and increase the energy saving of all stations, almost maintaining the performance of packet data transmissions.

Conclusions

A set of novel PHY-MAC cross-layer strategies have been described that improve system efficiency by automatic transmission rate adaptation. The proposed schemes have shown interesting properties that could be very useful for future multimedia wireless communication systems, where power efficiency of the handheld units will be a significant issue. The rate adaptation mechanism improves the spectrum efficiency, keeping the packet delay at the minimum possible value for each situation. On the other hand, the power-dependent strategies reduce the power consumption and intercell interference level for a packet-switched CDMA access network, where power control is essential for system efficiency.

References

[1] M. Zorzi and R. R. Rao, "Error Control and Energy Consumption in Communications for Nomadic Computing," *IEEE Trans. Comp.*, vol. 46, Mar. 1997, pp. 279–89.

[2] C. Chien *et al.*, "Adaptive Radio for Multimedia Wireless Links," *IEEE JSAC*, vol. 17, no. 5, May 1999, pp. 793–813.

[3] C. Liu and H. Asada, "A Source Coding and Modulation Method for Power Saving and Interference Reduction in DS-CDMA Sensor Network Systems," *Proc. Amer. Control Conf. 2002*, vol. 4, pp. 3003–08.

[4] D. Novakovic and M. Dukic, "An Algorithm for Combined Power Control and Base Station Assignment in Reverse Cellular DS-CDMA Link," *IEEE 6th Int'l. Symp. Spread Spectrum Techniques and Apps.*, vol. 2, 2000, pp. 786–89.

[5] E. S. Jung and N. H. Vaidya, "An Energy Efficient MAC Protocol for Wireless LANs," *IEEE INFOCOM 2002*, New York, June 2002, pp. 1756–64.

[6] I. Chlamtac, C. Petrioli, and J. Redi, "Energy-conserving Selective Repeat ARQ Protocols for Wireless Data Networks," *IEEE PIMRC '98*, vol. 2, Sept. 1998, pp. 836–40.

[7] A. Salkintzis and C. Chamzas, "Performance Analysis of a Downlink MAC Protocol with Power-Saving Support," *IEEE Trans. Vehic. Tech.*, vol. 49, no. 3, May 2000.

[8] P. Nuggehalli, V. Srinivasan, and R. Rao, "Delay Constrained Energy Efficient Transmission Strategies for Wireless Devices," *IEEE INFOCOM 2002*, vol. 3, pp. 1765–72.

[9] L. Alonso, R. Agusti, and O. Sallent, "A Near-optimum MAC Protocol Based on the Distributed Queuing Random Access Protocol (DQRAP) for a CDMA Mobile Communication System," *IEEE JSAC*, vol. 18, no. 9, Sept. 2000, pp. 1701–18.

[10] E. S. Sousa, "Interference Modeling in a Direct-Sequence Spread-Spectrum Packet Radio Network," *IEEE Trans. Commun.*, vol. 38, no. 9, Sept. 1990, pp. 1475–82.

[11] J. Rulnick and N. Bambos, "Mobile Power Management for Maximum Battery Life in Wireless Communication Networks," *IEEE INFOCOM '96*, vol. 2, Mar. 1996, pp. 443–50.

Biographies

LUIS ALONSO [M'99] (luisg@tsc.upc.es) received his Ph.D. in telecommunications engineering from the Universitat Politècnica de Catalunya (UPC), Spain, in 2001, where he has been an associate professor since 1998. He participates in research programs and projects funded by the European Union and the Spanish Government, and also collaborates with some telecommunications companies. His current research interests are in the field of medium access protocols, radio resource management, and QoS features for all kind of wireless communications systems.

RAMON AGUSTI [M'78] (ramon@tsc.upc.es) received his Ph.D. in telecommunication engineering from the Universitat Politècnica de Catalunya (UPC), Spain, in 1978 and he became full professor in 1987. For the last 15 years, he has been mainly concerned with the mobile communication systems. He has published more than 100 papers in these areas. He participated in the European program COST 231 and COST 259 as the Spanish representative delegate as well as in the RACE, ACTS, and IST European research programs. In this time he has also been an advisor to Spanish and Catalonian governmental agencies (DGTel, CICYT, ANEP, and CIRIT) on issues concerning radio and mobile communications. His actual research interest includes radio networks, wireless access protocols, radio resource management, and QoS.