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COST 2100 TD(08) 641  
Lille, France  
2008/October/6-8

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EURO-COST

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## **On the Fading Margin Gain due to Multi-Slot FEC in TDMA Broadcast Systems**

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# On the Fading Margin Gain due to Multi-Slot FEC in TDMA Broadcast Systems

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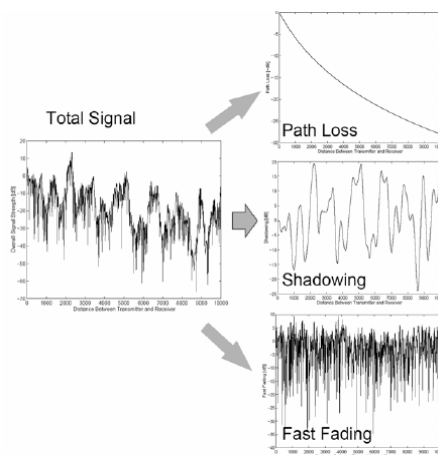
**Abstract:** *In this paper we derive the fading margin gain that can be achieved with multi-slot Forward Error Correction (FEC) in a generic Time Division Multiple Access (TDMA) broadcast system as a function of the number of slots encoded jointly (encoding period) and coding rate devoted to cope with shadowing.*

## I. INTRODUCTION

In wireless broadcast communication systems, Forward Error Correction (FEC) mechanisms protect loss events on underlying levels without a need for feedback, and rely on the transmission of redundant repair information (parity data), such that the receiver can detect and possibly correct errors occurred during the transmission.

However in the field mobile users typically experience spatial fading effects when moving across the service area due to the superposition of the multiple propagation paths between transmitter and receiver, such that transmission errors due to the impairments of the radio channel are correlated and several consecutive packets are lost. This reduces the FEC coding efficiency if the coded data is sequentially transmitted in spite of a large error correction capability. In order to protect the transmission against burst errors, FEC mechanisms are usually jointly implemented with time interleaving techniques, which distribute the coded data over time.

The wireless channel is traditionally modeled with three different processes: path loss, slow or long-term fading (shadowing), and fast or multipath fading, see Fig. 1 [1]. All of these processes vary as the positions of the transmitter and receiver change, and as any contributing object between the antennas is moved.



**Fig. 1:** Wireless channel as a superposition of path loss, shadowing and fast fading [1].

The path loss is the overall decrease in field strength as the distance between the transmitter and the receiver increases. The physical processes behind it are the outward spreading of the radio waves from the transmit antenna and the obstructing effects of trees and buildings. For large distances, the received signal strength decreases exponentially with the distance.

The shadowing models the deviations from the mean distance-dependent signal level due to the particular obstructions (clutters) between the transmitter and the receiver. It changes more rapidly than the path loss, with significant variations over distances of several tens of meters (comparable to the widths of buildings in the region of the mobile). The shadowing is traditionally taken to be log-normally distributed. That is, the distribution of the signal power is log-normal (the signal measured in dB follows a normal or Gaussian distribution). Hence it is also sometimes referred as log-normal fading.

Finally the fast fading accounts for the signal level fluctuations due to the constructive and destructive superposition of the multiple signals reaching the mobile. Fast fading involves variations on the scale of a half-wavelength and frequently introduces variations as large as 35 to 40 dB. The variation of the attenuation in dB is typically characterised by a Rice distribution under line of sight (LoS) conditions, and by a Rayleigh distribution under non-line of sight (NLoS) conditions.

In case of fast fading, a short time interleaving is required in order to average out the fading statistics (in the order of few to several ms depending on the user velocity and operating frequency). Interleaving is, however, typically not a feasible way to deal with shadowing, since the size of the interleaver would be huge. Moreover the imposed delay would not be acceptable in many cases. The traditional approach consists in adding an extra fading margin of several dBs to the link budget in order to assure a reliable communication with a given probability at the cell edge. Nevertheless, it is in principle possible to reduce the required fading margin taking advantage of the spatial diversity introduced by the mobility of the users using a FEC scheme spanning a sufficiently long time. This requires a powerful encoding algorithm capable of efficiently handling very large source blocks, as well as large memory capabilities at the terminals.

However recent advances in FEC mechanisms such as Raptor coding [2] make this possibility a reality for services with no real-time requirements, as they can be implemented in the upper layers in software without the need of dedicated software.

Indeed newly deployed Time Division Multiplex Access (TDMA) broadcast systems such as DVB-H (Digital Video Broadcasting – Handhelds) [3] and DVB-SH (Digital Video Broadcasting - Satellite services to Handheld devices) [4] include an optional multi-slot FEC based on Raptor codes in the upper layers to cope with shadowing.

In this paper we investigate the reduction in the fading margin that can be achieved with multi-slot FEC in a generic TDMA broadcast system as a function of the coding rate devoted to cope with shadowing and number of slots encoded jointly (encoding period). The gain will depend on the statistical correlation of the shadowing between consecutive slots. The lower the correlation between reception conditions, the higher the gain. We will also show that the gain depends on the standard deviation of the shadowing and the target coverage probability.

## II. PROBLEM DESCRIPTION

We consider a generic TDMA broadcast system where the different services are transmitted at the same frequency but in different time-slots. Without loss of generality we assume that the cycle time between slots of the same service,  $T_c$ , is constant. The system is characterized by a receiver sensitivity  $P_{s,\min}$ , minimum signal level at which reception is possible. Fast fading is assumed to be eliminated at the physical layer with some form of FEC and short time interleaving during the slot duration. Shadowing is assumed to remain constant during this time.

The variations of the shadowing in dB are described by a zero-mean Gaussian random variable with standard deviation  $\sigma_l$  and correlation distance  $d_{corr}$ . The standard deviation of the shadowing distribution is known as the location variability, and it determines the spread of the signal field strength around the mean value. Its value increases with frequency, being greatest in suburban areas and smallest in open areas (it is usually in the range of 5 to 12 dB). On the other side, the spatial correlation is modeled as a first-order exponential model [5]:

$$\rho(d) = e^{-d/d_{corr}} \quad (1)$$

where  $d_{corr}$  is distance taken for the autocorrelation to fall by  $e^{-1}$ .

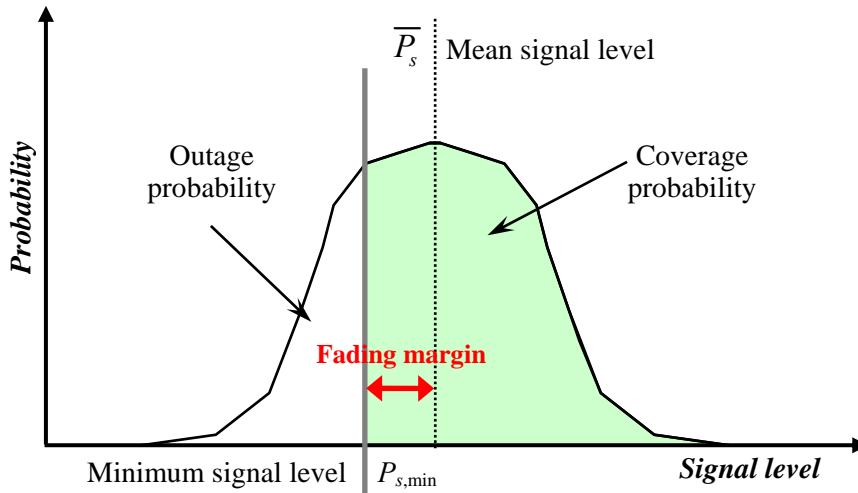
Shadowing makes coverage prediction statistical, such that it is predicted the signal availability rather than the signal level. The outage probability at a single reception point with an average signal level  $\bar{P}_s$  is equal to the probability that the shadowing increases the median path loss by at least  $\bar{P}_s - P_{s,\min}$  dB (see Fig. 2), and is given by:

$$\text{Outage Probability} = Q\left(\frac{\bar{P}_s - P_{s,\min}}{\sigma_l}\right). \quad (2)$$

Where the  $Q(\cdot)$  function is the complementary cumulative normal distribution:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt. \quad (3)$$

Values for  $Q(\cdot)$  can be calculated from the standard cumulative error (*erfc*) function.



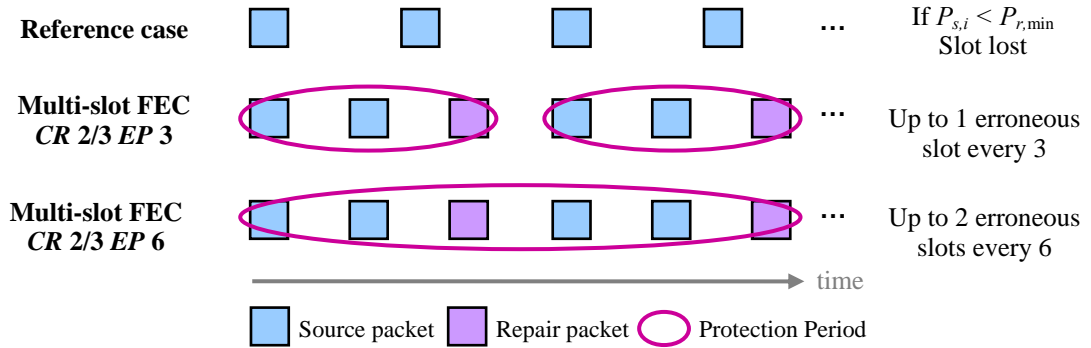
**Fig. 2:** Shadowing fading margin: outage and coverage probability concept.

The fading margin (also known as correction location factor in broadcasting) required to assure a reliable communication with a given probability at the cell edge can be easily computed as:

$$C_l = \mu \cdot \sigma_l. \quad (4)$$

where  $\mu$  is the distribution factor that depends on the coverage probability target. It is equal to 0.52 for 70%, 1.28 for 90%, 1.64 for 95%, and 2.33 for 99%. As an example, the normal value used with outdoor broadcasting signals in the UHF band is 5.5 dB, and hence in DVB-H usually a 9 dB fading margin is added to the link budget for 95% outdoor coverage availability (12 dB for 99%) [6].

We consider a multi-slot FEC operating in any upper layer above the physical layer meant to cope with shadowing. The multi-slot FEC configuration parameters are its coding rate and the interleaving depth in number of slots encoded jointly (encoding period). The error correction capability depends on the coding rate, but the transmission robustness depends also on the encoding period. The larger the encoding period, the more robust the transmission. An illustrative example is depicted in Fig. 3.



**Fig. 3:** Multi-slot FEC concept and error correction capability in a generic TDMA broadcast system.

For the reference case, if the received signal strength is lower than the receiver sensitivity the slot will be lost. With multi-slot FEC it is possible to cope to some extent with temporal slot losses.

The error correction capability will depend on both coding rate and encoding period, but the actual gain will depend on the distribution of the transmission errors over time. In the example shown in the figure, a coding rate 2/3 can correct up to 33% errors (assuming an ideal code), and thus it will be possible to recover from one erroneous slot every three (for  $EP$  3), two erroneous slots every six (for  $EP$  6) and so on, if all other slots within the encoding period are correctly received.

Multi-slot FEC can be used to reduce the fading margin due to shadowing to achieve a given coverage probability. The gain will increase for more robust coding rates and larger interleaving depths, and the maximum gain will occur when there is no correlation between reception conditions of consecutive slots.

### III. THEORETICAL ANALYSIS WITH UNCORRELATED SHADOWING

First we investigate the maximum fading margin gain that can be achieved with multi-burst slot FEC as a function of the coding rate and the encoding period in slot units. The maximum gain occurs when there is no shadowing correlation between reception conditions of consecutive slots.

#### A. Performance Evaluation

In this case the analysis can be derived analytically using the well-known Gilbert-Elliott (GE) channel model. The GE model dates back to the early 60's [7]-[8]. In this model for a slowly varying channel, the channel is assumed to be either in a good state where the error rate is small, or in a bad state where the error rate is large. The GE model is depicted in Fig. 4.

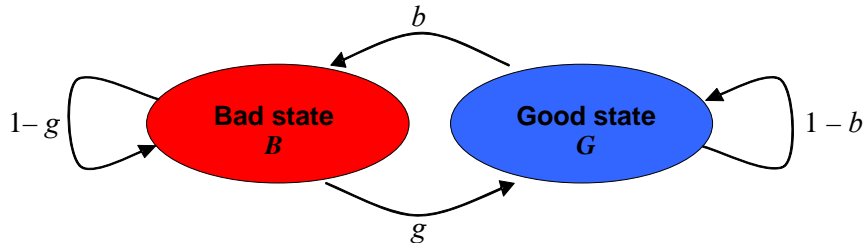


Fig. 4: The Gilbert-Elliott channel.

We denote the good and the bad state  $G$  and  $B$  respectively, and the probabilities that the channel changes from the good state to the bad state and vice versa  $b$  and  $g$  respectively. The stationary probabilities that the channel is in the good and the bad state are:

$$\begin{aligned} P^\infty(G) &= g/(b+g) \\ P^\infty(B) &= b/(b+g) \end{aligned} \quad (5)$$

In our case, as there is no correlation between consecutive time-slots, the GE channel is memoryless, and the probability of being in the good or bad state is independent of the previous state. The GE channel becomes memoryless when  $g + b = 1$ . We further assume that the probability of erasure is 1 in the bad state and 0 in the good state. Therefore,  $g$  and  $b$  are the coverage and outage probabilities respectively.

Under these conditions, if the GE channel is observed at  $n$  consecutive instants of time, the probability that the channel is in the bad state  $d$  times,  $0 \leq d \leq n$ , is given by:

$$P_n(d) = \binom{n}{d} \cdot g^{(n-d)} \cdot (1-g)^d \quad (6)$$

With multi-slot FEC, given the coding rate ( $CR$ ) and the encoding period ( $EP$ ), the minimum number of time-slots needed to decode a source block can be easily computed as:

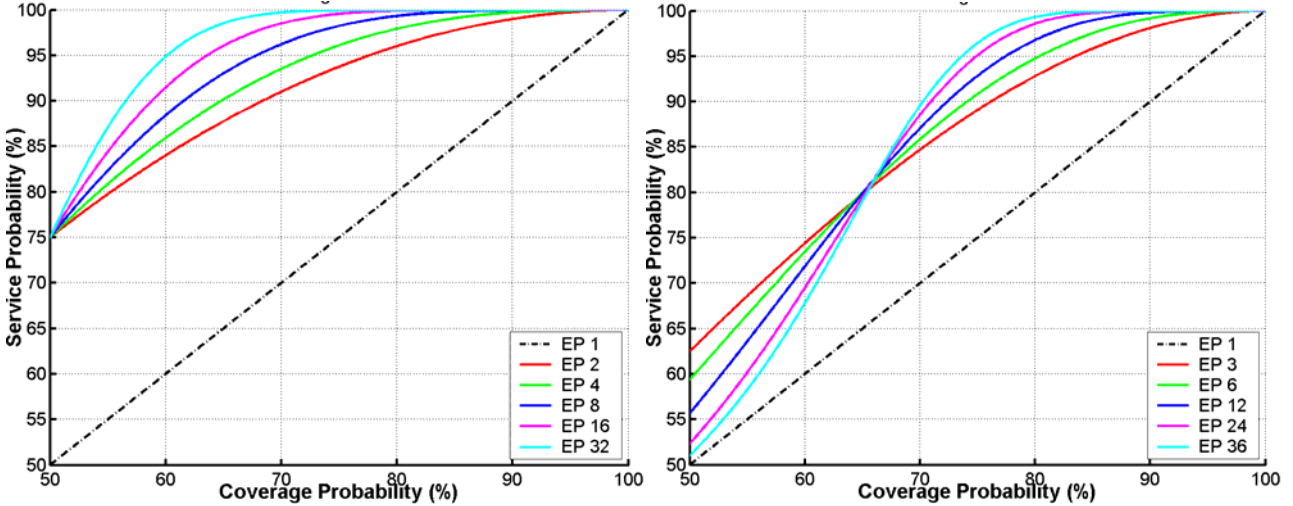
$$NrSlots_{\min} = \lceil EP \cdot CR \rceil \quad (7)$$

where  $\lceil \cdot \rceil$  is the ceiling function. Finally, the service probability, defined as the probability of receiving a time-slot correctly, can be computed as:

$$\text{Service Probability} = 1 - \sum_{i=NrSlots_{\min}+1}^{EP} P_{EP}(i) \cdot \frac{i}{EP} \quad (8)$$

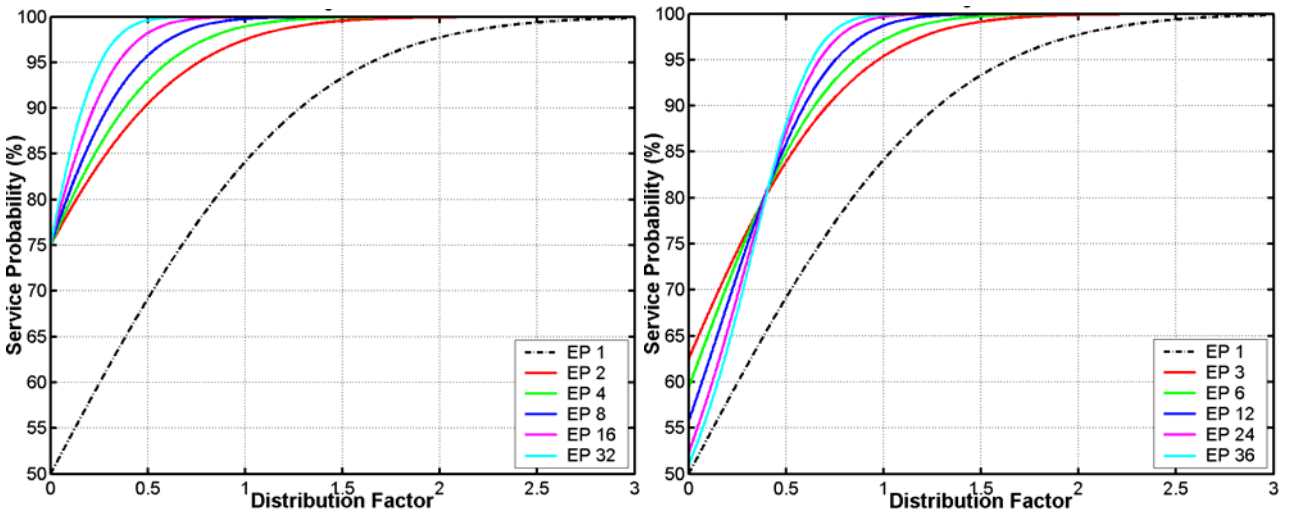
### B. Analytical Results

Equation (8) relates the gain due to multi-slot FEC in terms of increased probability of receiving correctly a time-slot for a given coverage probability (area actually covered with a signal level higher than the receiver sensitivity). Fig. 5 shows the service probability as a function of the coverage probability for a multi-slot FEC with coding rate 1/2 and 2/3 for different encoding periods.



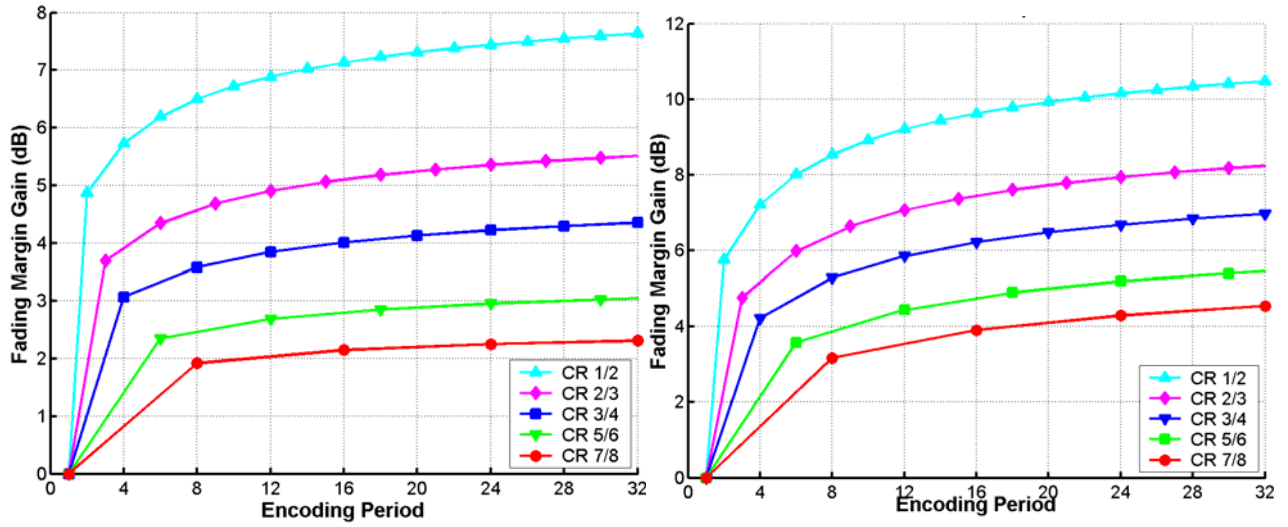
**Fig. 5:** Service probability vs. Coverage probability. Coding rate 1/2 (left) and 2/3 (right).

In the figure we can clearly see how the coverage perceived by the mobile users is increased reducing the coding rate and increasing the encoding period. Hence, there is no need to guarantee very high coverage levels to achieve a given QoS target (service probability). The reduction in the area coverage can be translated into a reduction of the fading margin. From the results shown in Fig. 5, it can be obtained a new distribution factor for computing the fading margin, see Fig. 6. The fading margin gain will be thus proportional to the standard deviation of the shadowing.



**Fig. 6:** Service probability vs. Distribution factor  $\mu$ . Coding rate 1/2 (left) and 2/3 (right). Fading margin is  $\mu$  times  $\sigma_l$ .

Finally, we present fading margin gain results for  $\sigma_l$  5.5 and service probabilities of 95% and 99%.



**Fig. 7:** Fading margin gain (dB) for 95% (left) and 99% (right) service probability vs. Encoding period in slot units. Uncorrelated shadowing:  $\sigma_l$  5.5 dB,  $d_{corr}$  0 m.

We can see that the gain obtained is very significant, even for small interleaving depths, especially for coding rates 1/2 and 2/3. Moreover, we can also note that the gain increases for more demanding QoS criteria, and gains for 99% service probability are between 1 dB and 3 dB larger than for 95%.

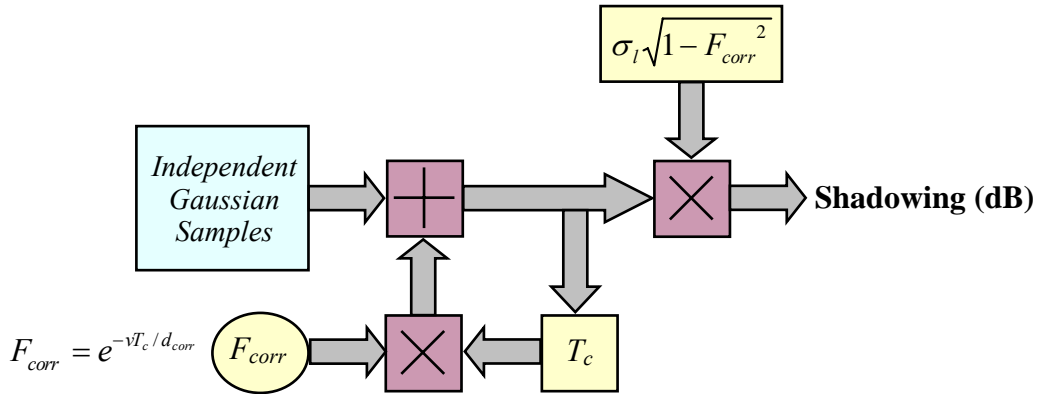
## IV. SIMULATION ANALYSIS WITH CORRELATED SHADOWING

### A. Performance Evaluation

Next, we investigate fading margin gains due to multi-slot FEC with correlated shadowing. In general the assumption that the shadowing is uncorrelated between consecutive time-slots will not apply in most cases.

The shadowing correlation between consecutive time-slots depends on the shadowing correlation distance, the cycle time between slots, and the user velocity, see (1). The gains will be smaller than the ones shown in Fig. 7, and will decrease for larger shadowing correlation distances and smaller user velocities and cycle time values. However it should be clear that the maximum gain does not depend on these parameters, and they basically determine the level of time interleaving required for achieving a given gain. Indeed all three parameters can be combined into one: the ratio between the moved distance by the user during the cycle time and the shadowing correlation distance,  $d/d_{corr}$ .

Although it has been proposed to use the GE model to analytically investigate the effect of correlated shadowing in [9], it cannot completely capture the exponential correlation property of the shadowing. Therefore, we evaluate the performance of multi-slot FEC under correlated shadowing by means of Monte-Carlo simulations. To simulate correlated shadowing we employ the methodology proposed in [1], and depicted in Fig. 8.

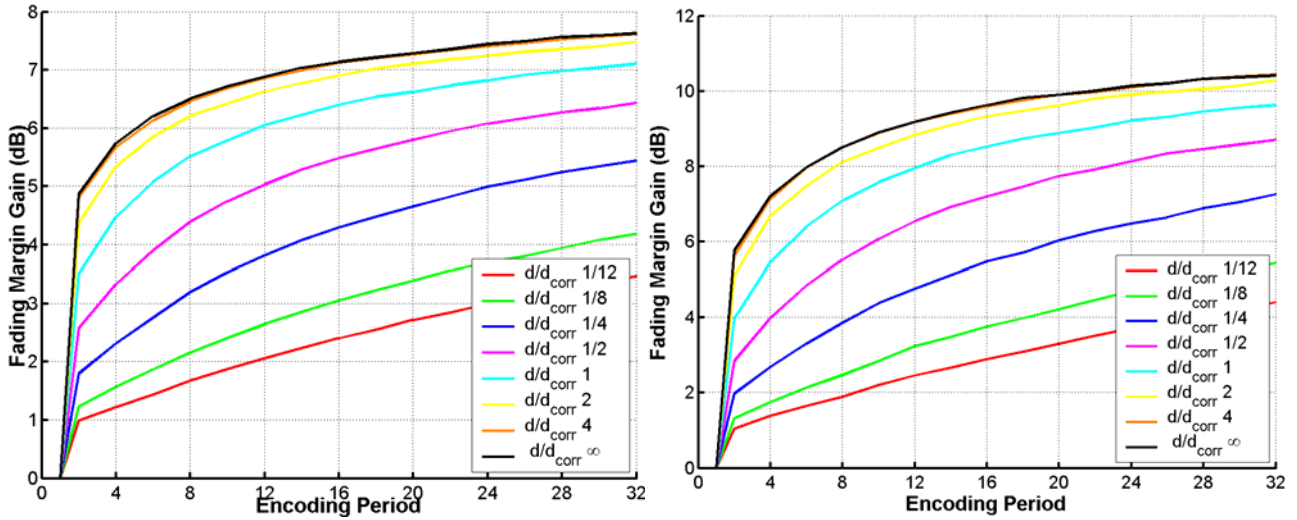


**Fig. 8:** Method for simulating correlated shadowing. Simulation parameters: shadowing standard deviation  $\sigma_l$ , shadowing correlation distance  $d_{corr}$ , and user velocity  $v$ .

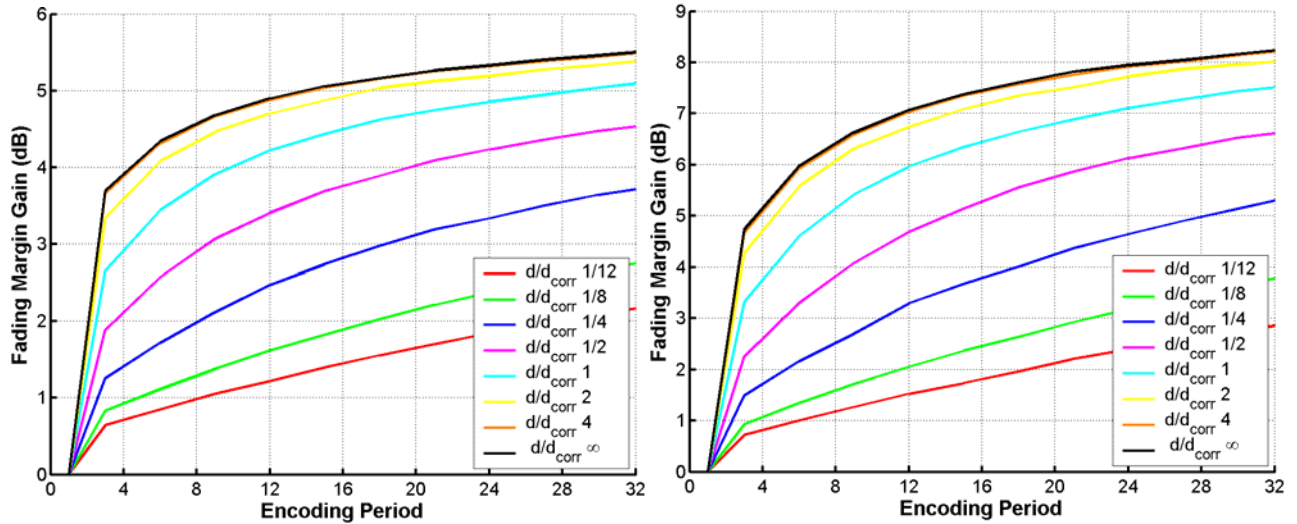
### B. Simulation Results

Figures 9 and 10 show the fading margin gain with correlated shadowing as a function of the interleaving depth for coding rates 1/2 and 2/3 respectively for service probabilities of 95% and 99% (again,  $\sigma_l$  is 5.5 dB). In the figures we can see how the gain decreases when the correlation between consecutive bursts increases. Obviously for fully static reception conditions ( $d/d_{corr} = 0$ ), there is no gain by performing a multi-slot protection of the transmission.

Here we can clearly see why multi-slot FEC is especially suited for vehicular users, as they will experience a less correlated shadowing process due to their high speeds, achieving very significant gains for relatively small encoding periods. On the other hand pedestrian users will usually require relatively large encoding periods due to their reduced mobility.



**Fig. 9:** Fading margin gain (dB) vs. Encoding period in slot units. Service probability 95% (left) and 99% (right). Coding rate 1/2. Correlated shadowing:  $\sigma$  5.5 dB.



**Fig. 10:** Fading margin gain (dB) vs. Encoding period in slot units. Service probability 95% (left) and 99% (right). Coding rate 2/3. Correlated shadowing:  $\sigma$  5.5 dB.

## ACKNOWLEDGMENTS

This work has been partially supported by the Spanish Ministry of Industry, Tourism and Commerce under the project FURIA (Futura Red Integrada Audiovisual), <http://www.furiapse.com>.

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