IMPROVING DOWNLINK PERFORMANCE IN CELLULAR RADIO COMMUNICATIONS

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RÉSUMÉ

Nous présentons une méthode de codage conjoint de messages dans le cas d'utilisateurs multiples, conçue particulièrement pour le canal descendant des systèmes radio-cellulaires. Elle utilise une connaissance de la réponse des canaux pour tirer profit des différences d'atténuations dûes aux pertes de trajet. Nous traitons le modèle du canal le plus simple, soit un canal gaussien à temps discret sans effets d'évanouissement ni d'interférences intra-céllulaires. En considérant le canal descendant d'un système avec deux utilisateurs comme un *canal de diffusion*, nous montrons que d'importantes améliorations en termes de capacité peuvent-être obtenues par rapport au *multiplexage orthogonal (MO)*. Par la suite, nous étudions le gain de codage fourni par cette méthode par rapport à un système MO sans codage. Finalement, nous décrivons une modification de cette méthode pour un grand nombre d'utilisateurs sans augmentation significative de la complexité.

ABSTRACT

In this work we consider a multiuser coding technique applied to the downlink in cellular radio communications. This technique uses channel knowledge at the transmitter to take advantage of inevitable differences in channel attenuations due to path loss. We restrict ourselves to the simplest channel model, namely a non-fading discrete-time Gaussian channel without inter-cell interference. Using the *Broadcast Channel* model for the downlink of a two-user system, we show that significant improvement in terms of capacity can be obtained using such techniques in comparison to *Orthogonal Multiplexing(OM)*. We then consider the coding gain of this system compared to uncoded OM. Finally, we describe how this technique can be extended to many users without a significant increase in complexity.

1 INTRODUCTION

In cellular communications there are two primary communication links between the cell's central basestation and the users, the *uplink* (or reverse link) and the *downlink* (or forward link). The former refers to the flow of information from the users to the basestation, and is a problem which has been and is still today the subject of much debate. The downlink, however, receives less attention, since to some extent it is a simpler problem. The main reason being the inherent synchronism between the users signals. In a single-cell scenario we only have the problem of transmitting a single signal containing the information for all the users to the collection of users located within the cell's boundary. In this work we restrict ourselves to this situation.

Ignoring time-variation effects due to fading, the downlink in cellular communications is an example of a *Gaussian Broadcast Channel*. The general broadcast channel is still an open problem in information theory, but fortunately in this case the capacity region is known. It is a different problem than the one encountered in the uplink (which is an example of a gaussian *multiuser channel*), and despite many similarities, should be treated differently. In order to achieve capacity, a joint coding technique known as *cooperative broadcasting* [2][3] can be employed. Cellular systems in use today usually employ some form of orthogonal multiplexing (OM) in the downlink. The aim of this work is to show that it might be worthwhile to consider a non-orthogonal coded-modulation approach.

It turns out that the problem of joint coding for cellular broadcast channels is closely related to the problem of *unequal error protection*. This is a coding scheme in which composite messages are coded such that the different components are protected unequally according to their importance. In HDTV broadcast channels or coded speech this technique can be very useful, since different parts of the transmitted message have varying sensitivity to noise [4,5]. In the cellular broadcast situation we have a similar problem; the *near-in* users receive the composite message from the basestation with less attenuation than the *far-out* users and therefore require less error-protection on their message component. Linked with the unequal coding of the message is the idea of power control. In order to code message components appropriately, the signal power at the receivers must be fed back to the basestation. Fortunately this can be achieved via the uplink.

2 Gaussian Broadcast Channel

In this section we consider the capacity of the gaussian broadcast channel for orthogonal multiplexing (OM) and cooperative broadcasting (CB) schemes. We restrict ourselves to the two-user discrete-time case, since this can be extended to many users and continuous-time easily.

On the transmission end, a composite discrete-time signal, s_j, is sent with power E. The signals received at the terminals are attenuated by factors β_i, $i = 0, 1$ which are due to the path loss between the basestation and the terminals. The received signals are therefore

$$y_j = \sqrt{\beta_i E} s_j + n_{ij} \qquad i = 0, 1 \tag{1}$$

where n_{ij} is additive white gaussian noise with variance σ_i^2. For simplicity of notation, we incorporate the β_i into the noise variances.

We begin by examining the simplest OM situation, namely non-naive TDMA or unequal time-sharing. Let $C_0(\gamma_0)$ and $C_1(\gamma_1)$ be the single-user capacities for the two users,

$$C_i(\gamma_i) = \frac{1}{2}\log(1+\gamma_i) , \tag{2}$$

where $\gamma_i = E/\sigma_i^2$ is the signal-to-noise ratio (SNR) for user i. With unequal time-sharing, the transmitted symbols are shared such that the message for user 0 is transmitted a proportion α of the total transmit time. The remainder of the time is reserved for user 1. The capacity region is expressed as

$$\begin{aligned} R_0 &< \frac{\alpha}{2}\log(1+\gamma_0) \\ R_1 &< \frac{(1-\alpha)}{2}\log(1+\gamma_1) , \end{aligned} \tag{3}$$

where R_i is the information rate for user i.

Next consider an orthogonal multiplexing scheme based on *Hadamard* sequences, which is what is used in the IS-95 standard. The transmitted signal over two symbols is as follows

$$s_j = \sqrt{\alpha E} x_{0j}\begin{bmatrix}1 & 1\end{bmatrix} + \sqrt{(1-\alpha)E} x_{1j}\begin{bmatrix}1 & -1\end{bmatrix} \tag{4}$$

where E is the total energy per transmitted symbol, and α is the proportion of E alloted to user 0. The terminals see the signals

$$\begin{aligned} y_{0j} &= s_j + n_{0j} \\ y_{1j} &= s_j + n_{1j} , \end{aligned} \tag{5}$$

where n_{ij} is a gaussian random vector with independent components and component variance σ_i^2. After demultiplexing, we have the following single-user channels,

$$\begin{aligned} u_0 &= s_j\begin{bmatrix}1\\1\end{bmatrix} = 2\sqrt{\alpha E} x_0 + \eta_0 \\ u_1 &= s_j\begin{bmatrix}1\\-1\end{bmatrix} = 2\sqrt{(1-\alpha)E} x_1 + \eta_1 , \end{aligned} \tag{6}$$

where η_i is a gaussian random variable with variance $2\sigma_i^2$. Since one bit per user is transmitted over 2 symbols, we have that the capacity region is given by

$$\begin{aligned} R_0 &< \frac{1}{4}\log(1+2\alpha\gamma_0) \\ R_1 &< \frac{1}{4}\log(1+2(1-\alpha)\gamma_1) . \end{aligned} \tag{7}$$

Finally, we examine the CB approach, where, the transmitted signal is given by

$$s_j = \sqrt{\alpha E} x_{0j} + \sqrt{(1-\alpha)E} x_{1j} . \tag{8}$$

Here, a joint decoding strategy is employed: the user on the weaker channel decodes his signal considering the other user's signal as part of the noise. The user on the stronger channel first decodes the weaker user's signal, subtracts it out from the received signal and then decodes his own signal. It was shown that this is the optimal scheme for the gaussian broadcast channel. The capacity region (for $\gamma_0 < \gamma_1$) is defined as follows [1]

$$\begin{aligned} R_0 &< \frac{1}{2}\log\left(1 + \frac{\alpha\gamma_0}{1+(1-\alpha)\gamma_0}\right) \\ R_1 &< \frac{1}{2}\log(1+(1-\alpha)\gamma_1) . \end{aligned} \tag{9}$$

Although the capacity region is the most informative measure of the performance of a system, it is more instructive to look at the intersection point of the $R_0 = R_1$ line and the boundary of the region. This defines the maximum of achievable rate at which both users can transmit, which is what we will call the capacity C and is shown in Fig. 1.

In order to operate at this point on the capacity region boundary, feedback of the received powers is needed, which implies a sort of power control. In contrast to the multiuser channel where power control attempts to force all users to have the same signal power at the

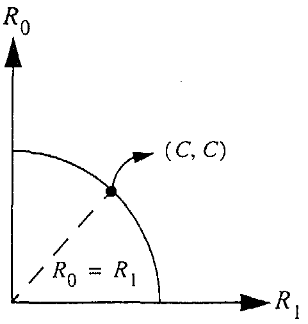

Figure 1: Broadcast Channel Capacity

receiver, power control on the broadcast channel refers choosing the proportion of the total power (or total time for TDMA) alloted to each of the users.

In Fig. 2 we compare the capacities of cooperative broadcasting and OM systems on gaussian broadcast channels. When the two channel attenuations are equal, the capacities are the same. This, however, is a very unlikely situation, since in contrast to the case of the uplink, we cannot control the received power ratio between the terminals. As the channel attenuation ratio increases we see that the cooperative broadcasting system performs significantly better than the other two. We may conclude, therefore, that even a sub-optimal cooperative broadcasting system could still significantly outperform an optimal TDMA or OM system. We examine this issue in the following section.

It is interesting to note that the OM system that we described here performs significantly worse than unequal TDMA. We should mention, however, that implementing a TDMA scheme of this type would be quite difficult since it would require a variable rate coding scheme (i.e. the user on the stronger channel would use a signal constellation with many points for a short time, and the user on the weaker channel would use a constellation with few points for a longer time.) It turns out that when we examine the capacity region for the three schemes, the OM scheme will generally extend beyond the limits of the TDMA boundary, however it does so in a region which favours one user heavily. In the equal rate region it is always worse than TDMA.

3 A Simple Joint Coding Scheme

The joint coding scheme which is implied in the formulation of the capacity region of the broadcast channel is, in essence, *unequal error protection*. We can think of the signal destined for the user on the weaker channel as the message component which has to be protected more heavily than the signal destined for the user on the stronger channel. These types of cod-

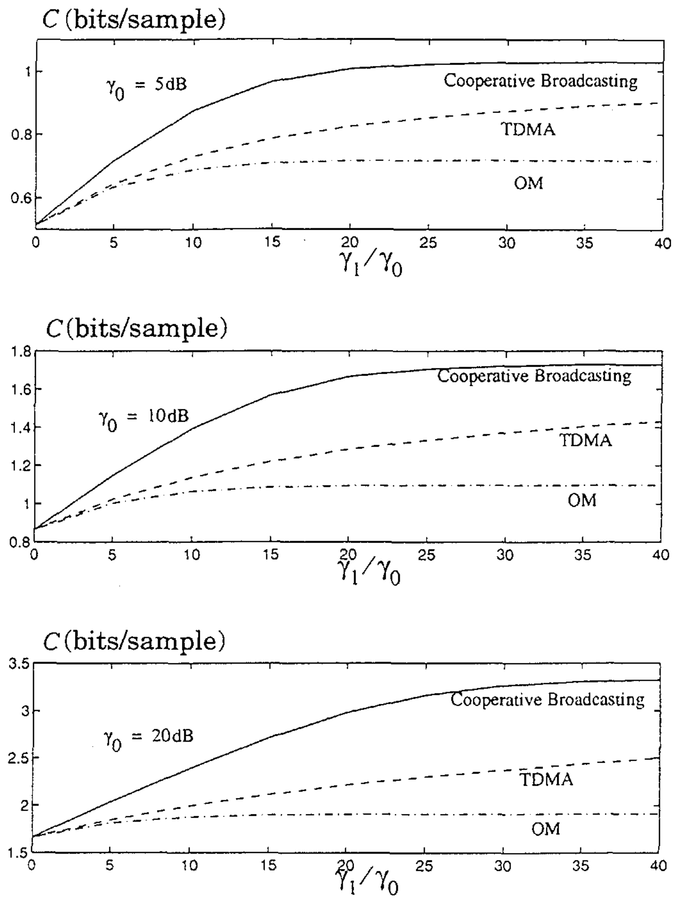

Figure 2: Capacity Comparison of Cooperative Broadcasting, TDMA and OM

ing schemes are particularly useful in other broadcast channel applications, most notably HDTV broadcasting or channel coding for speech signals[4,5].

Here we present a simple joint coding scheme for realizing some of the attainable improvement shown in Fig. 2. Assume that the x_{ij} in (4) and (8) are antipodal (± 1) signals. For the OM scheme, we have that the bit error rates are given by

$$\begin{aligned} P_{e0} &= Q\left(\sqrt{4\alpha\gamma_0}\right) \\ P_{e1} &= Q\left(\sqrt{4(1-\alpha)\gamma_1}\right) \end{aligned} \qquad (10)$$

so that when α is chosen such that the two terminals have the same bit error-rate, this bit error-rate is given by

$$P_e = Q\left(\sqrt{\left(\frac{4\gamma_R}{1+\gamma_R}\right)\gamma_0}\right) \qquad (11)$$

where $\gamma_R = \gamma_1/\gamma_0$. We should point out that choosing the correct value for α implies a sort of power control, since it requires knowledge of the received SNR at the terminals. For the joint coding system the composite signal points (assuming $\alpha < 1/2$) are shown in Fig. 3. Assume that the x_{ij} are both encoded with the same rate 1/2 convolutional code with minimum free dis-

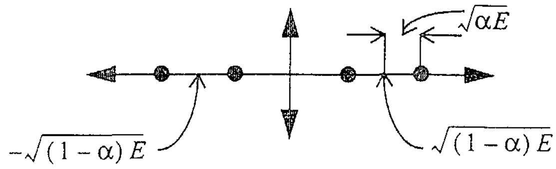

Figure 3: Composite Signal Constellation

tance d_{free} and that $\gamma_0 \ll \gamma_1$. Clearly this system has the same spectral efficiency as OM. Decoding is performed as follows (it is not optimal): the terminal on the weaker channel decodes his message (x_{0j}) ignoring the component intended for the other terminal. The terminal on the stronger channel decodes the other message first, subtracts it out from the received signal, and proceeds to decode his own message (x_{1j}). The bit error-rate for the two users is

$$\begin{aligned} P_{e0} &< Q\left(\sqrt{2\gamma_0 d_{free}(\sqrt{1-\alpha}-\sqrt{\alpha})^2}\right) \\ P_{e1} &< Q\left(\sqrt{2\gamma_1 d_{free}\alpha}\right) \end{aligned} \tag{12}$$

Again, choosing α such that both terminals have the same bit error-rate, we have

$$\alpha = \frac{1}{\gamma_R + 2\sqrt{\gamma_R} + 2}, \tag{13}$$

which not surprisingly is not 1/2 when $\gamma_R = 1$. The bit error-rate for this joint decoding scheme is bounded by

$$P_e < Q\left(\sqrt{\frac{2d_{free}\gamma_R}{\gamma_R + 2\sqrt{\gamma_R} + 2}\gamma_0}\right). \tag{14}$$

The coding gain of the joint coding system with respect to OM is therefore

$$G_c = \frac{(1+\gamma_R)\,d_{free}}{2\left(\gamma_R + 2\sqrt{\gamma_R} + 2\right)} \tag{15}$$

This is plotted in Fig. 4 for a few values of d_{free}. We see that as the ratio of received power levels increases, significant improvement is attained, at the expense of increased receiver complexity.

We have found that in order to extend this scheme to more than two users, it is necessary to increase the number of signalling dimensions. At the same time, however, we do not want the decoding process to become too complex, since the processing is done at the terminals. The receiver complexity would be too great if more than a few users were coded/decoded jointly. A practical alternative, therefore, would be to combine this joint coding/decoding scheme with an orthogonal multiplexing scheme in the following way: the set of users are grouped in pairs, such in each pair one user has a strong channel and the other has a weak channel. Each pair is jointly coded and then all the pairs are multiplexed with OM. The pairs are

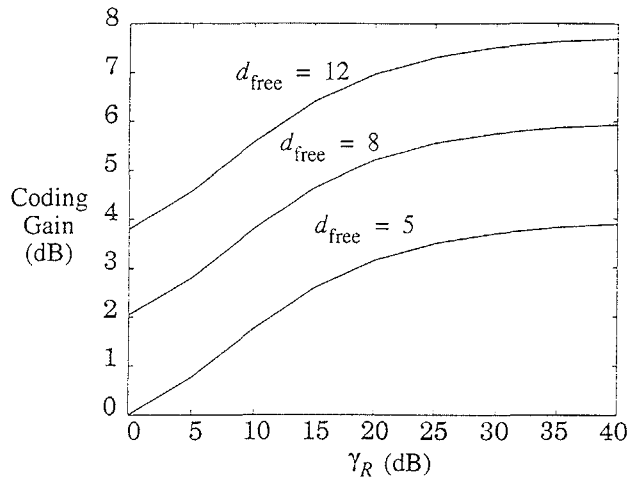

Figure 4: Coding gain of joint coding over OM

formed in this fashion to maximize the performance of the system, which increases with the ratio of the channel strengths.

4 Discussion

We have shown that significant improvement can be obtained by using this simple joint coding technique compared with uncoded OM. One may wonder, however, whether it is really worthwhile to use this approach, since we could simply use a rate 1/2 QPSK code instead of uncoded BPSK with OM and obtain similar coding gains. This is true, but we must take into account the fact that we double the number of signalling dimensions by going to QPSK. For a fair comparison, therefore, we would have use a joint coding/decoding approach with a rate 1/4 QPSK code which would clearly yield even larger coding gains. We are currently investigating more elaborate coding schemes such as this to achieve increased performance both in power and spectral efficiency.

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