Inter-Cell Interference Coordination for Multimedia Communications

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***Abstract*—In this paper, we study the inter-cell interference coordination for the transmission of progressive images which need unequal spectral efficiencies in the bitstream. Based on our analysis for the outage probabilities of the full and partial frequency reuses, we suggest the use of fractional frequency reuse for the transmission of a series of progressive packets.**

I. Introduction

The growing demand for multimedia services has invoked intense research on cross-layer design. In this paper, we study the effect of the frequency reuse on the performance of the transmission of progressive images which need unequal spectral efficiencies in the bitstream. We analyze the crossover of the outage probabilities for the full and partial frequency reuses. It is proven that the crossover point in signal-to-noise ratio (SNR) is a strictly increasing function in spectral efficiency. We consider an orthogonal frequency-division multiplexing (OFDM) system that can support either full or partial frequency reuse for its subcarriers. Based on our analysis, we propose the fractional frequency reuse for the transmission of progressive images.

II. System model

Let $N_{\rm rf}$ denote the frequency reuse factor. The $N_{\rm rf} = 1$ yields the full frequency reuse, and $N_{\rm rf} > 1$ yields the partial frequency reuse. Let W denote the bandwidth per user within a cell. Then, each user is able to use a bandwidth of $W/N_{\rm rf}$. The downlink transmissions in neighboring cells that use the same frequency band as the target cell are averaged at a user, and this yields the interference to a user. In this paper, we consider the hexagonal planar cellular system where a base station is assumed to be located in the center of each cell. For such a system, the distance between the centers of the nearest cells (i.e., the nearest base stations) that use the same frequency band is given by $2d_{\rm cell}\sqrt{N_{\rm rf}}$ [1], where $d_{\rm cell}$ is the distance between the center and the edge of the cell. From this, the distance between the user in a target cell and the base station of the i th nearest interfering cell can be expressed as

$$D_{{\rm user},i} = 2d_{\rm cell}\sqrt{N_{\rm rf}} + d_{{\rm user},i} \tag{1}$$

where $d_{{\rm user},i}$ is the distance parameter which specifies the location of the user in a target cell, from the viewpoint of the base station in the ith nearest interfering cell. The range of $d_{{\rm user},i}$ is given by $-2d_{\rm cell}/\sqrt{3} \le d_{{\rm user},i} \le 2d_{\rm cell}/\sqrt{3}$, which is determined by the size of the cell.

Suppose that a user is at a distance x from the base station. The signal transmitted from the base station is received at the user with an attenuation of a factor $x^{-\alpha}$ in power. Also suppose that all the base stations in the cellular system transmit the signals with the same power P. Then, from (1), the received power of the interference signal that comes from the ith nearest interfering cell can be expressed as

$$I_i = \frac{P}{D^{\alpha}_{{\rm user},i}} = \frac{P}{d^{\alpha}_{\rm cell}} \cdot \frac{1}{\left(2\sqrt{N_{\rm rf}} + r_{{\rm user},i}\right)^{\alpha}} \tag{2}$$

where $r_{{\rm user},i}$ is the normalized distance parameter which is defined by $r_{{\rm user},i} = d_{{\rm user},i}/d_{\rm cell}$ with the range given by $-2/\sqrt{3} \le r_{{\rm user},i} \le 2/\sqrt{3}$. In a model where the interference signals come from only the nearest interfering cells, the power of total out-of-cell interference can be expressed as

$$I = \sum_{i=1}^{N_{\rm cell}} I_i = \frac{P}{d^{\alpha}_{\rm cell}} f_{\rm I}(N_{\rm rf}, \mathbf{r}_{\rm user}, \alpha) \tag{3}$$

where $N_{\rm cell}$ denote the number of the nearest interfering cells and $f_{\rm I}(N_{\rm rf}, \mathbf{r}_{\rm user}, \alpha)$ is defined by

$$f_{\rm I}(N_{\rm rf}, \mathbf{r}_{\rm user}, \alpha) = \sum_{i=1}^{N_{\rm cell}} \frac{1}{\left(2\sqrt{N_{\rm rf}} + r_{{\rm user},i}\right)^{\alpha}} > 0 \tag{4}$$

where $\mathbf{r}_{\rm user} = [r_{{\rm user},1}, \ldots, r_{{\rm user},N_{\rm cell}}]$ is the normalized distance parameter vector, and the inequality follows from $N_{\rm rf} \ge 1$ and $-2/\sqrt{3} \le r_{{\rm user},i} \le 2/\sqrt{3}$. For the downlink of target cell, we consider a system with a single transmit and $N_{\rm r}(\ge 1)$ receive antennas communicating over a frequency flat fading channel.

III. The Outage Probabilities for the Full and Partial Frequency Reuses

We analyze the crossover point of the outage probabilities for the full and partial frequency reuses. The received signal to interference and noise ratio (SINR) at the user, which is at a distance x from the base station of a target cell, can be expressed as

$$\text{SINR} = \frac{\gamma \|\mathbf{H}\|_F^2}{\frac{1}{N_{\rm rf}} + \gamma\, \beta^{\alpha} f_{\rm I}(N_{\rm rf}, \mathbf{r}_{\rm user}, \alpha)} \tag{5}$$

where $\|\cdot\|_F$ denotes the Frobenius norm, $W/N_{\rm rf}$ is the bandwidth assigned to each user, $\gamma = P/x^{\alpha} N_0 W (> 0)$ is the received SNR at the user, and $\beta = x/d_{\rm cell}$ is the user's normalized distance from the base station. The range of β is given by $0 < \beta \leq 2/\sqrt{3}$. From (5), the outage probability is given by [2]

$$P_{\text{out}}(\gamma) = \Pr\left[\frac{W}{N_{\text{rf}}}\log_2\left(1 + \frac{\gamma\|\mathbf{H}\|_F^2}{\frac{1}{N_{\text{rf}}} + \gamma\,\beta^\alpha f_{\text{I}}(N_{\text{rf}}, \mathbf{r}_{\text{user}}, \alpha)}\right) < R\right] \tag{6}$$

where R is the transmission data rate of the user (bits/s). For a wideband system with full frequency reuse, we set $N_{\text{rf}} = 1$ in (6). Then, the outage probability of the wideband system, denoted by $P_{\text{out,w}}(\gamma)$, can be derived. For a narrowband system with partial frequency reuse, we set $N_{\text{rf}} = n(> 1)$ in (6). Then, we can obtain the outage probability of the narrowband system, which is denoted by $P_{\text{out,n}}(\gamma)$. We find the SNR, γ^*, for which $P_{\text{out,w}}(\gamma)$ and $P_{\text{out,n}}(\gamma)$ are identical:

$$P_{\text{out,w}}(\gamma^*) = P_{\text{out,n}}(\gamma^*) \quad \text{for } \gamma^* > 0 \tag{7}$$

It can be shown that the existence of the crossover point in SNR, γ^*, is summarized as follows:

1) γ^* is given by

$$\gamma^* = \frac{\frac{1}{n}\left(\sum_{k=1}^{n} 2^{\frac{(n-k)R}{W}}\right) - 1}{\beta^\alpha\left[f_{\text{I}}(1, \mathbf{r}_{\text{user}}^{\text{w}}, \alpha) - f_{\text{I}}(n, \mathbf{r}_{\text{user}}^{\text{n}}, \alpha)\left(\sum_{k=1}^{n} 2^{\frac{(n-k)R}{W}}\right)\right]} \tag{8}$$

and $\gamma^* > 0$ if and only if $\sum_{k=1}^{n} 2^{\frac{(n-k)R}{W}} < f_{\text{I}}(1, \mathbf{r}_{\text{user}}^{\text{w}}, \alpha)/f_{\text{I}}(n, \mathbf{r}_{\text{user}}^{\text{n}}, \alpha)$ or, equivalently, if and only if $R < R^*$, where R^* is the data rate which satisfies the following equality

$$\sum_{k=1}^{n} 2^{\frac{(n-k)R^*}{W}} = \frac{f_{\text{I}}(1, \mathbf{r}_{\text{user}}^{\text{w}}, \alpha)}{f_{\text{I}}(n, \mathbf{r}_{\text{user}}^{\text{n}}, \alpha)} \tag{9}$$

2) γ^* is given by (8), and $\gamma^* < 0$ if and only if $\sum_{k=1}^{n} 2^{\frac{(n-k)R}{W}} > f_{\text{I}}(1, \mathbf{r}_{\text{user}}^{\text{w}}, \alpha)/f_{\text{I}}(n, \mathbf{r}_{\text{user}}^{\text{n}}, \alpha)$ (or, equivalently, $R > R^*$).

3) γ^* does not exist if and only if $\sum_{k=1}^{n} 2^{\frac{(n-k)R}{W}} = f_{\text{I}}(1, \mathbf{r}_{\text{user}}^{\text{w}}, \alpha)/f_{\text{I}}(n, \mathbf{r}_{\text{user}}^{\text{n}}, \alpha)$ (or, equivalently, $R = R^*$).

Note that $\gamma^* < 0$ implies that the crossover point of $P_{\text{out,w}}(\gamma)$ and $P_{\text{out,n}}(\gamma)$ does not exist in the range of $\gamma > 0$.

Moreover, it can be shown that the crossover point in SNR, γ^*, is a strictly increasing function in $R > 0$ as long as $\gamma^* > 0$ holds (i.e., the crossover point exists in the range of $\gamma > 0$).

Next, we compare the outage probabilities, $P_{\text{out,w}}(\gamma)$ and $P_{\text{out,n}}(\gamma)$, for the full and partial frequency reuses, respectively. It can be proven that

- If $R < R^*$, then

$$\begin{aligned} P_{\text{out,n}}(\gamma) &< P_{\text{out,w}}(\gamma) \quad \text{for } \gamma > \gamma^* > 0 \\ P_{\text{out,n}}(\gamma) &> P_{\text{out,w}}(\gamma) \quad \text{for } 0 < \gamma < \gamma^* \end{aligned} \tag{10}$$

- If $R \geq R^*$, then either $\gamma^* < 0$, or γ^* does not exist. For this case, we have

$$P_{\text{out,n}}(\gamma) > P_{\text{out,w}}(\gamma) \quad \text{for } \gamma > 0 \tag{11}$$

IV. Fractional Frequency Reuse for the Transmission of Progressive Images

Based on the analysis in the previous section, we propose the fractional frequency reuse for the transmission progressive images which need unequal spectral efficiencies in the bitstream. Progressive encoders employ a mode of transmission so that encoded data have gradual differences of importance in their bitstreams [3]. Suppose that the system takes the bitstream from the progressive source encoder, and transforms it into a sequence of N_P packets. We suppose that each of these N_P progressive packets can be encoded with different transmission data rates, as well as can be transmitted over the subcarriers with different frequency reuses, so as to yield the best end-to-end performance. The error probability of an earlier packet needs to be lower than or equal to that of a later packet, due to the gradually decreasing importance in the progressive bitstream. Thus, given the same transmission power, the earlier packet requires a transmission data rate which is lower than or equal to that of the later packet.

Suppose that the kth packet in a sequence of N_P packets is transmitted with full frequency reuse. Then, our analysis tells us that the k + 1st, k + 2nd, …, N_Pth packets also should adopt full frequency reuse rather than partial one. This is because in Section III we have shown that, when full frequency reuse is preferable for a packet with a data rate of R_1, a packet with R_2 ($> R_1$) also should employ full frequency reuse, as long as the transmission power of the latter is the same as or smaller than that of the former. That is, in a sequence of N_P progressive packets, the last i consecutive packets should adopt full frequency reuse, and the other $N_P - i$ packets should employ partial frequency reuse ($0 \leq i \leq N_P$). Our strategy, i.e., the transmission of progressive packets over the subcarriers with their frequencies being unequally reused, is based on the gradual differences of importance in the progressive bitstream, which results in unequal spectral efficiencies for a sequence of packets. Our strategy is effective as long as the data rate gradually increases in a series of packets.

V. Conclusions

We analyzed the behavior of the crossover point of the outage probability curves for full and partial frequency reuse in terms of the spectral efficiency. Exploiting this, we proposed the fractional frequency reuse for the transmission of a sequence of progressive packets.

References

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